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SPECIFICATION

TITLE OF THE INVENTION

VIRTUAL VIEWPOINT IMAGE GENERATION METHOD
AND THREE-DIMENSIONAL IMAGE DISPLAY METHOD AND
5   APPARATUS

TECHNICAL FIELD

The present invention relates to a
technology for estimating information on a three-
10 dimensional shape of an object from plural images to
generate an image using the information. The
technology of the present invention can be applied
to a system that supports visual communications such
as a TV phone and the like.

15

BACKGROUND ART

From the past, in the fields of the
computer graphics (CG) and the virtual reality (VR),
technologies have been activity studied for
20 generating an image of an object, by a computer,
viewed not only from a viewpoint position at which a
camera is placed but also from a viewpoint position
desired by a user.

For example, there are methods for
25 displaying a three-dimensional image of an object or
generating an image (to be referred to as a virtual
viewpoint image hereinafter) of an object viewed
from a virtual viewpoint using plural images of the
object taken under different conditions.

30 As a method for displaying a three-
dimensional image of an object, there is a method
using a display having plural image display planes
such as a DFD (Depth-Fused 3-D) display, for example.
The DFD is a display in which plural image display
35 planes are layered at some intervals (for example,
refer to document 1: Japanese Patent No.3022558).
The DFD can be roughly classified into a brightness

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modulation type and a transmission type.

For displaying an image of the object on the DFD, a two-dimensional image of the object is displayed on each image display plane. At this time,
5   if the DFD is the brightness modulation type, brightness of each of pixels overlapping when viewed from a predetermined viewpoint of an observer (reference viewpoint) is set in a ratio according to the shape of the object in the depth direction for
10   displaying the pixels. Accordingly, as to a point existing on the object, brightness of the pixel on an image display plane existing near from the observer becomes large, and as to another point, the brightness of the pixel on a display plane existing
15   farther from the observer becomes large. As a result, the observer who observes images displayed on each image display plane of the DFD can see a stereoscopic image (three-dimensional image) of the object.
20   When the DFD is the transmission type, transmittance of each of pixels, on each image display plane, overlapping when viewed from a predetermined viewpoint of the observer (reference viewpoint) is set according to the shape of the
25   object in the depth direction so as to display the pixels.

In addition to the displaying method using the DFD, as the method for displaying the three-dimensional image of the object, there is a method
30   for displaying two images having parallax corresponding to an interval of right and left eyes of the observer on a screen such as a liquid crystal display and the like.

For generating the images for displaying
35   the three-dimensional image of the object or for generating the image of the object viewed from arbitrary viewpoints, when the three-dimensional

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shape of the object is known since the object is
generated by a computer graphics and the like, for
example, each of the images can be generated using
the model. On the other hand, when the three-
5 dimensional shape of the object is not known, it is
necessary to obtain the three dimensional shape of
the object, namely, a geometrical model of the
object before generating each image.

     In addition, also when generating the
10 virtual viewpoint image using the plural images, it
is necessary to obtain the geometrical model of the
object based on the plural images first. The
geometrical model of the object is represented as a
set of basic figures called polygon or voxel, for
15 example.

     There are various methods for obtaining
the geometrical model of the object based on the
plural images, and many studies are being performed
as Shape from X in the field of the computer vision.
20 In the Shape from X, the stereo method is a
representative model obtaining method (refer to
document 2 : Takeo Kanade et al.:"Virtualized
Reality: Constructing Virtual Worlds from Real
Scenes," IEEE MultiMedia, Vol.4, No.1, pp.34-37,
25 1997, for example).

     In the stereo method, the geometrical
model of the object is obtained based on plural
images of the object taken from different viewpoints.

     At this time, a distance from the
30 reference viewpoint for obtaining the model to each
point of the object is calculated using
triangulation techniques by performing corresponding
point matching, that is, by associating points
(pixels) on each image. But, the geometrical model
35 of the object is not immediately obtained using the
stereo method. A group of points on the surface of
the object is obtained. Therefore, it is necessary

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to determine structural information indicating how
the points included in the point group are connected
and what surface is formed in order to obtain the
geometrical model of the object (refer to document
5   3 : Katusi Ikeuchi "Model generation of real object
using images", Journal of the Robotics Society of
Japan, Vol.16, No.6, pp.763-766, 1998, for example).
        That is, in the method for obtaining the
geometrical object using the stereo method, the
10   apparatus (computer) for generating the image should
perform complicated processing such as application
of the shape of the object, statistical processing
and the like. Therefore, high computing power is
necessary.
15   In addition, as the method for obtaining
the geometrical model of the object based on the
plural images, there is a method called Shape from
Silhouette for determining a region that the object
occupies in the space based on an outline of the
20   object in each image taken from plural viewpoints
(to be referred to as Shape from Silhouette method
hereinafter) (refer to document 4: Potmesil,
M: "Generating Octree Models of 3D Objects from
their Silhouettes in a Sequence of Images," CVGIP 40,
25   pp.1-29, 1987, for example).
        In many cases, the geometrical model of
the object obtained by the Shape from Silhouette
method is represented as a set of small cubes called
voxels. However, when the geometrical model of the
30   object is represented by the voxels, large amount of
data are required for representing the three-
dimensional shape of the object. Therefore, high
computing power is required for obtaining the
geometrical model of the object using the Shape from
35   Silhouette method.
        Therefore, in recent years, instead of
representing the geometrical model of the object

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using polygons or voxels like the stereo method and the Shape from Silhouette method, a method is proposed in which partial images of the object are texture-mapped to projection planes having a multi-
5   layered structure so as to represent the three-dimensional shape of the object on the multi-layered planes (refer to document 5: Jonathan Shade et al.:"Layered Depth Images," SIGGRAPH98 Conference Proceedings, pp.231-242, 1998, and document 6: Tago,
10 Nitta, Inamura, Harashima, "Video-Based Rendering using dynamic layer representation", Three-dimensional image conference 2001, pp.33-36, 2001, for example).
        The texture mapping is a method for
15 setting the projection planes of the multi-layered structure, and mapping each partial image (texture image) cut out from the taken image to a projection plane corresponding to a distance of the object appearing in the texture image so as to obtain
20 stereoscopic visual effects. Thus, this method has advantages in that adequately high-speed processing can be performed even by graphics hardware in a generally widespread personal computer and in that handling of data is easy.
25   However, on the other hand, when representing the geometrical model of the object using the multi-layered planes based on the texture mapping, if intervals at which the projection planes are set are too wide, detailed shape of the object
30 cannot be represented. Therefore, a contrivance is proposed in which a value (depth value) in addition to color information of R (red), G (green) and B (blue) is added for each pixel of the texture image for detailed shape, for example, while rough shape
35 is represented by the projection planes (planes). In the document 5, a method is proposed in which positions of pixels of each texture image are

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changed according to the depth value so as to
represent detailed depths that cannot be fully
represented only by the multi-layered planes. In
addition, in the document 6, a method is proposed in
5   which transmittance of each pixel is set according
to the depth value to represent detailed depths that
cannot be fully represented only by the multi-
layered planes.

10   DISCLOSURE OF THE INVENTION
PROBLEM TO BE SOLVED BY THE INVENTION
However, in the above-mentioned methods
for obtaining the geometrical model of the object,
the method for obtaining the geometrical model of
15   the object using the stereo method is susceptible to
the shape of the object and the texture of the
surface of the object, and surrounding environment
of the object so that highly reliable information is
not necessarily obtained for any shape of the object
20   and for every point of the object (refer to document
7 : Masatoshi Okutomi: "Why is stereo difficult?",
Journal of the Robotics Society of Japan, Vol.16,
No.6, pp.39-43, 1998, for example).
When estimating the distance of the object,
25   if the reliability of the estimation is low, there
is a case that erroneous distance is estimated.
When the estimated distance is erroneous,
discontiguous noise appears in positions at which
the estimation of the distance is erroneous in a
30   virtual viewpoint image generated using the
geometrical model of the object, for example.
Therefore, the virtual viewpoint image appears that
a lost region 7B occurs in a part of the object 7 as
shown in Fig.1. In addition, according to the
35   principle of the Shape from Silhouette method, the
geometrical model of the object is obtained assuming
that the object is gibbous. Therefore, there is a

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problem in that a correct model of the object cannot
be obtained when the object is wholly or partially
concave.

In addition, according to the Shape from
5   Silhouette method, it is difficult in itself to
correctly extract the outline of the object against
the background on the image. Thus, the method for
correctly extracting the outline is a main research
task in the computer vision field now as in the past.
10   That is, the geometrical model of the object
obtained by the Shape from Silhouette method is a
model obtained from an inaccurate outline, and the
reliability is not high. Therefore, there is a
problem in that the image generated from the
15   geometrical model of the object obtained by the
Shape from Silhouette method does not have
sufficiently satisfactory quality.

In addition, as to the method for
representing the three-dimensional shape of the
20   object using multi-layered planes like the texture
mapping, the depth value provided for each texture
pixel is known. That is, the method assumes that
the shape of the object is accurately obtained.
Therefore, when the shape of the object is not known,
25   it is necessary to obtain the geometrical model of
the object first. As a result, when there is an
unreliable portion in the shape estimation of the
object, there is a case that the texture image is
mapped to an incorrect projection plane, so that
30   there is a problem in that the generated image is
remarkably deteriorated.

In addition, in the method for
representing the three-dimensional shape of the
object using texture mapping, processing for mapping
35   images on the multi-layered projection planes can be
performed at high speed. However, higher processing
ability is required for accurately obtaining the

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shape of the object in the processing for obtaining the depth values.

As described above, according to the conventional technologies, when there is an

5   unreliable portion in estimation of the shape of the object, estimation of distance is tend to be incorrect, so that there is a problem in that discontiguous noise occurs on the generated image and the image quality is deteriorated.

10   In addition, it is necessary to increase reliability of estimation for avoiding deterioration of image quality due to estimation error of the shape of the object. For this purpose, it is necessary to use many images and perform strict

15   computational processing so as to obtain the accurate geometrical model of the object. However, in this case, high processing ability (computational power) is necessary for the apparatus that generates the virtual viewpoint image and the like. Thus,

20   there is a problem in that it is difficult for the generally used personal computer to generate the virtual viewpoint image having few deterioration at high speed.

In addition, for increasing reliability of

25   the geometrical model of the object, pictures taken from more viewpoints are necessary. Thus, there is a problem in that the image taking apparatus becomes large and the apparatus configuration is complicated.

An object of the present invention is to

30   provide a technology that can decrease remarkable deterioration of image quality that occurs at a part where the reliability of estimation of the shape of the object is low when generating the image of the object by obtaining the three-dimensional shape of

35   the object from plural images.

Another object of the present invention is to provide a technology that can generate the image

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having small partial deterioration of image quality
in a short time even by using an apparatus having
low processing performance when generating the image
of the object by obtaining the three-dimensional
5   shape of the object from plural images.
Still another object of the present
invention is to provide a technology that can
downsize an image-taking apparatus for taking images
used for obtaining the geometrical model of the
10 object so as to simplify the apparatus configuration.
Before-mentioned and other objects, and
new features of the present invention will become
more apparent from the following detailed
description when read in conjunction with the
15 accompanying drawings.

MEANS FOR SOLVING THE PROBLEM
To solve the above-mentioned problem, the
present invention is configured as a virtual
20 viewpoint image generation method including:
a step of obtaining plural images of an
object taken by plural cameras;
a step of determining a virtual viewpoint
that is a position from which the object is viewed;
25 and
a step of generating a virtual viewpoint
image that is an image of the object viewed from the
virtual viewpoint based on the obtained images of
the object,
30 the step of generating the virtual
viewpoint image including:
a step 1 of setting projection planes
having a multi-layered structure;
a step 2 of obtaining each corresponding
35 point, on the images of the object, corresponding to
a projection point of a projection plane;
a step 3 of determining color information

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or brightness information of each projection point based on color information or brightness information of corresponding points;

5   a step of calculating, for each of the projection points overlapping when viewed from a reference viewpoint in a space, a degree of probability that the object exists at a distance corresponding to a position of the projection point based on a degree of correlation of the
10 corresponding points or neighborhoods of the corresponding points;

      a step 5 of performing mixing processing on color information or brightness information of reference points overlapping when viewed from the
15 virtual viewpoint according to the degree of probability of existence of the object so as to determine color information or brightness information of each pixel of the virtual viewpoint image; and

20   a step 6 of repeating steps from the step 1 to the steps 5 for every point corresponding to pixels of the virtual viewpoint image.

      In addition, the image generation method of the present invention can be configured as an
25 image generation method including:

      a step of obtaining images of an object taken from different viewpoints;

      a step of obtaining a three-dimensional shape of the object based on the images; and

30   a step of generating an image of the object viewed from a viewpoint of an observer based on the obtained three-dimensional shape of the object,

      the step of obtaining the three-
35 dimensional shape of the object including:

      a step of setting projection planes having a multi-layered structure in a virtual three-

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dimensional space;

a step of determining a reference viewpoint for obtaining the three-dimensional shape of the object;

5　a step of determining color information or brightness information of projection points that are points on the projection planes based on color information or brightness information of corresponding points, on the obtained images,

10　corresponding to the projection points;

a step of calculating correlation degrees among corresponding points corresponding to the projection points;

a step of calculating, for each of the

15　projection points overlapping when viewed from the reference viewpoint, an existence probability that is a probability that the object exists at the projection point based on the correlation degree of each projection point;

20　the step of calculating the correlation degree including:

a step of preparing plural groups of camera sets each being a group of some viewpoints selected from the plural viewpoints; and

25　a step of obtaining the correlation degree from the corresponding points on images included in each camera set,

the step of determining the existence probability including:

30　a step of calculating the existence probability based on the correlation degree of each projection point obtained for each camera set; and

a step of determining the existence probability of each projection point by performing

35　integrating processing for the existence probability determined for each camera set.

In addition, the present invention can

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be configured as an image generation method
including:

a step of obtaining images of an object
taken by changing focusing distance;

5   a step of obtaining a virtual viewpoint
that is a viewpoint from which the object appearing
in the images is viewed;

a step of obtaining a three-dimensional
shape of the object based on the images; and

10   a step of generating an image of the
object viewed from the virtual viewpoint based on
the obtained three-dimensional shape of the object,

the step of obtaining the three-
dimensional shape of the object including:

15   a step of setting projection planes having
a multi-layered structure in a virtual three-
dimensional space;

a step of determining a reference
viewpoint for obtaining the three-dimensional shape

20   of the object;

a step of determining color information or
brightness information of projection points, that
are points on the projection planes, based on color
information or brightness information of

25   corresponding points, on the obtained images,
corresponding to the projection points;

a step of determining focusing degrees of
the projection points based on focusing degrees of
the corresponding points corresponding to the

30   projection points;

a step of calculating, for each of the
projection points overlapping when viewed from the
reference viewpoint, an existence probability that
is a probability that the object exists at a

35   distance corresponding to a position of the
projection point based on the focusing degree of
each projection point;

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the step of generating the image of the object viewed from the virtual viewpoint including:

mixing color information or brightness information of the projection points overlapping
5   when viewed from the virtual viewpoint in a ratio corresponding to the existence probability to determine color information or brightness information of each point of the image to be generated.
10   In addition, the present invention can be configured as an image generation method including:

a step of obtaining images of an object taken under different conditions;

a step of obtaining a three-dimensional
15   shape of the object based on the images; and

a step of generating an image of the object viewed from a viewpoint of an observer based on the obtained three-dimensional shape of the object,
20   the step of obtaining the three-dimensional shape of the object including:

a step of setting projection planes having a multi-layered structure in a virtual three-dimensional space;
25   a step of determining a reference viewpoint for obtaining the three-dimensional shape of the object;

a step of determining color information or brightness information of projection points, that
30   are points on the projection planes, based on color information or brightness information of corresponding points, on the obtained images, corresponding to the projection points;

a step of determining, for each of the
35   projection points overlapping when viewed from the reference viewpoint, an existence probability that is a probability that a surface of the object exists

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at the projection point;

the step of determining the existence probability including:

a step of calculating an evaluation
5   reference value of each projection point from image information of the corresponding points;

a step of performing statistical processing on the evaluation reference value of each projection point; and

10   a step of calculating the existence probability of each projection point based on the evaluation reference value on which the statistical processing has been performed.

In addition, the present invention can be
15   configured as a three-dimensional image display method including:

a step of obtaining images of an object taken under different conditions;

a step of obtaining a three-dimensional
20   shape of the object based on the images;

a step of setting a viewpoint position from which an observer observes plural image display planes existing at different depth positions when viewed from the observer;

25   a step of generating two-dimensional images to be displayed on each image display plane based on the obtained three-dimensional shape of the object; and

a step of presenting a three-dimensional
30   image of the object by displaying the generated two-dimensional images on each display plane,

the step of obtaining the three-dimensional shape of the object including:

a step of setting projection planes having
35   a multi-layered structure in a virtual three-dimensional space;

a step of determining a reference

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viewpoint for obtaining the three-dimensional shape
of the object;

5
a step of determining color information or
brightness information of projection points, that
are points on the projection planes, based on color
information or brightness information of
corresponding points, on the obtained images,
corresponding to the projection points;

10
a step of determining, for each of the
projection points overlapping when viewed from the
reference viewpoint, an existence probability that
is a probability that a surface of the object exists
at the projection point;

15
the step of generating the two-dimensional
images including:

converting the color information or the
brightness information and the existence probability
of the projection point into color information or
brightness information and existence probability of

20
each display point that is a point on the image
display plane corresponding to the projection plane
on which the projection point exists so as to
generate the two dimensional images;

the step of presenting the three-

25
dimensional image of the object including:

displaying the color information or
brightness information on each display point with
brightness according to the existence probability.

30
EFFECT OF THE INVENTION

According to the present invention, when
generating the image of the object by obtaining the
three-dimensional shape of the object from plural
images, it becomes possible to reduce remarkable

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deterioration of image quality that occurs in a part
where the reliability of estimation of the shape of
the object is low. In addition, it becomes possible

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to generate the image having small partial
deterioration of image quality in a short time even
by using an apparatus having low processing
performance. Further, it becomes possible to
5   downsize a taking apparatus for taking images used
for obtaining the geometrical model of the object so
as to simplify the apparatus configuration.

BRIEF DESCRIPTION OF THE DRAWINGS
10   Fig.1 is a diagram for explaining problems
a conventional virtual viewpoint image;
            Fig.2 is a schematic diagram for
explaining the principle of the virtual viewpoint
image generation method of the first embodiment, and
15   is a diagram showing examples of projection plane
group, camera, reference viewpoint, projection point
and corresponding point;
            Fig.3A and Fig.3B are diagrams for
explaining the principle of the virtual viewpoint
20   image generation method of the first embodiment;
            Fig.4A and Fig.4B are diagrams for
explaining the principle of the virtual viewpoint
image generation method of the first embodiment, and
are diagrams showing an example of mixing processing
25   according to transparency of projection points;
            Fig.5 is a schematic diagram for
explaining the principle of the virtual viewpoint
image generation method of the first embodiment, and
is a diagram showing examples of object, projection
30   plane group, reference viewpoint, virtual projection
point and projection point;
            Fig.6 is a schematic diagram showing an
outline configuration of a virtual viewpoint image
generation apparatus of an embodiment 1-1, and is a
35   block diagram showing a configuration of the inside
of the image generation apparatus;
            Fig.7 is a schematic diagram showing an

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outline configuration of a virtual viewpoint image
generation apparatus of an embodiment 1-1, and is a
configuration example of a system using the image
generation apparatus;

5   Fig.8 is a schematic diagram for
explaining the mathematical principle model of the
virtual viewpoint image generation method using the
virtual viewpoint image generation apparatus of the
embodiment 1-1, and is a diagram showing an example
10   of projection conversion;

Fig.9 is a schematic diagram for
explaining the mathematical principle model of the
virtual viewpoint image generation method using the
virtual viewpoint image generation apparatus of the
15   embodiment 1-1, and is a diagram showing an example
of coordinates conversion;

Fig.10 is a schematic diagram for
explaining the generation processing procedure for
the virtual viewpoint image of the embodiment 1-1,
20   and is a flow diagram showing the whole generation
processing;

Fig.11 is a schematic diagram for
explaining the generation processing procedure for
the virtual viewpoint image of the embodiment 1-1,
25   and is a concrete flow diagram showing steps for
generating the virtual viewpoint image;

Fig.12 is a schematic diagram for
explaining the generation processing procedure for
the virtual viewpoint image of the embodiment 1-1,
30   and is a diagram showing an example of a setting
method of the projection plane;

Fig.13 is a schematic diagram for
explaining the generation processing procedure for
the virtual viewpoint image of the embodiment 1-1,
35   and is a diagram showing examples of projection
points, projection point series and a set of
projection point series;

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Fig.14 is a schematic diagram for
explaining the generation processing procedure for
the virtual viewpoint image of the embodiment 1-1,
and is a diagram showing examples of a reference
5   viewpoint, projection points and angles based on
various camera positions for explaining mixing
processing of color information;
Fig.15 is a schematic diagram for
explaining the generation processing procedure for
10   the virtual viewpoint image of the embodiment 1-1,
and is a diagram showing an example of corresponding
point matching processing;
Fig.16 is a schematic diagram for
explaining the generation processing procedure for
15   the virtual viewpoint image of the embodiment 1-1,
and is a diagram for explaining rendering
processing;
Fig.17 is a schematic diagram for
explaining the generation processing procedure for
20   the virtual viewpoint image of the embodiment 1-1,
and is a diagram showing an example of a generated
virtual viewpoint image;
Fig.18 is a schematic diagram showing an
application example of a system to which the virtual
25   viewpoint image generation apparatus of the
embodiment 1-1 is applied;
Fig.19A is a flow diagram indicating
processing that is a feature of the embodiment 1-2,
and Fig.19B is a flow diagram showing an example of
30   concrete processing procedure of steps for
determining transparency information;
Fig.20 is a schematic diagram for
explaining the virtual viewpoint image generation
method of the embodiment 1-3, and is a diagram
35   showing examples of projection plane group,
reference viewpoint, virtual viewpoint and
projection points;

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Fig.21 is a schematic diagrams for explaining the principle of the image generation method of the second embodiment, and is a diagram for explaining a concept of a method for generating
5   the image to be displayed;

Fig.22 is a schematic diagram for explaining the principle of the image generation method of the second embodiment, and is a diagram representing Fig.21 in two-dimensional;
10   Fig.23A and Fig.23B are diagrams for explaining a method for obtaining the correlation degree of the corresponding points;

Fig.24A and Fig.24B are diagrams for explaining a problem when obtaining the correlation
15 degree of the corresponding points;

Fig.25 is a schematic diagram for explaining the principle of the image generation method of the second embodiment, and is a diagram for explaining a method for solving the problem when
20 obtaining the correlation degree;

Fig.26A and Fig.26B are diagrams for explaining an example of a method for improving accuracy of the existence probability

Fig.27 is a schematic diagram for
25 explaining the principle of the image generation method of the second embodiment;

Fig.28 is a schematic diagram for explaining the principle of the image generation method of the second embodiment;
30   Fig.29 is a schematic diagram for explaining an image generation method of the embodiment 2-1, and is a flow diagram showing an example of a general processing procedure;

Fig.30 is a schematic diagram for
35 explaining an image generation method of the embodiment 2-1, and is a flow diagram showing an example of a processing procedure of steps for

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determining color information and existence
probability of projection points in Fig.29;

Fig.31 is a schematic diagram for
explaining an image generation method of the
5   embodiment 2-1, and is a flow diagram showing an
example of steps for determining the existence
probability in Fig.30;

Fig.32 is a schematic diagram for
explaining an image generation method of the
10   embodiment 2-1, and is a diagram showing an example
foe setting a camera set;

Fig.33 is a schematic diagram for
explaining an image generation method of the
embodiment 2-1, and is a diagram for explaining a
15   method for converting information of the projection
plane to information of display plane;

Figs.34A and 34B are diagrams for
explaining a method for converting information of
the projection plane to information of display
20   plane;

Fig.35 is a block diagram showing a
configuration example of the image generation
apparatus to which the image generation method of
the embodiment 2-1 is applied;

25   Fig.36 is a diagram showing a
configuration example of an image display system
using the image generation apparatus to which the
image generation method of the embodiment 2-1 is
applied;

30   Fig.37 is a diagram showing another
configuration example of an image display system
using the image generation apparatus to which the
image generation method of the embodiment 2-1 is
applied;

35   Fig.38 is a schematic diagram for
explaining an image generation method of the
embodiment 2-2, and is a flow diagram showing an

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example of the whole processing procedure;

Fig.39 is a schematic diagram for explaining an image generation method of the embodiment 2-2, and is a diagram for explaining a

5   principle of rendering;

Fig.40 is a schematic diagram for explaining an image generation method of the embodiment 2-2, and is a diagram for explaining problems that arise in the image generation method

10   in this embodiment;

Figs.41A and B are schematic diagrams for explaining an image generation method of the embodiment 2-2, and are diagrams for explaining a method for solving the problems that arise in the

15   image generation method in this embodiment;

Fig.42 is a schematic diagram for explaining an image generation method of the embodiment 2-2, and is a flow diagram showing an example of the processing procedure for converting

20   the existence probability to transparency;

Fig.43 is a schematic diagram for explaining the principal of the image generation method of the third embodiment, and is a diagram showing a setting example of the projection planes

25   and the reference viewpoint;

Fig.44 is a schematic diagram for explaining the principal of the image generation method of the third embodiment, and is a diagram showing a setting example of the projection planes

30   and the reference viewpoint;

Fig.45 is a schematic diagram for explaining the principal of the image generation method of the third embodiment, and is a diagram for explaining a method for determining the color

35   information and the focusing degree of the projection point;

Fig.46 is a schematic diagram for

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explaining the principal of the image generation
method of the third embodiment, and is a diagram for
explaining a method of determining the existence
probability of the projection point;

5   Fig.47 is a schematic diagram for
explaining the principal of the image generation
method of the third embodiment, and is a diagram for
explaining a method of determining the existence
probability of the projection point;

10   Fig.48 is a schematic diagram for
explaining the principal of the image generation
method of the third embodiment, and is a diagram for
explaining a method of determining the existence
probability of the projection point;

15   Fig.49 is a schematic diagram for
explaining the principal of the image generation
method of the third embodiment, and is a diagram for
explaining a method for generating an image viewed
from the virtual viewpoint;

20   Fig.50 is a schematic diagram for
explaining the principal of the image generation
method of the third embodiment, and is a diagram for
explaining problems in the image generation method
in the present invention;

25   Fig.51 is a schematic diagram for
explaining the principal of the image generation
method of the third embodiment, and is a diagram for
explaining a method for solving the problems in the
image generation method in the present invention;

30   Fig.52 is a schematic diagram for
explaining the mathematical model of the image
generation method of the third embodiment, and is a
diagram showing relationship among projection points,
corresponding points and points on the image to be

35 generated;
          Fig.53 is a schematic diagram for
explaining the mathematical model of the image

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generation method of the third embodiment, and is a
diagram for explaining a method for converting
points on the space to pixels on the image;

Fig.54 is a schematic diagram for
5   explaining the image generation method of the
embodiment 3-1, and is a a flow diagram showing a
generation procedure for the image;

Fig.55 is a schematic diagram for
explaining the image generation method of the
10   embodiment 3-1, and is a diagram for explaining a
method for setting the projection point series;

Fig.56 is a schematic diagram for
explaining the image generation method of the
embodiment 3-1, and is a flow diagram showing a
15   concrete example of processing of the step 10305 of
Fig.54;

Fig.57 is a schematic diagram for
explaining the image generation method of the
embodiment 3-1, and is a diagram for explaining a
20   rendering method;

Fig.58 is a schematic diagram showing a
general configuration of the apparatus for
generating the image using the image generation
method of the embodiment 3-1, and is a a block
25   diagram showing the configuration of the apparatus;

Fig.59 is a diagram for explaining a
configuration example of the object image taking
means the embodiment 3-1;

Fig.60 is a diagram for explaining a
30   configuration example of the object image taking
means the embodiment 3-1;

Fig.61 is a diagram for explaining a
configuration example of the object image taking
means the embodiment 3-1;

35   Fig.62 is a schematic diagram showing a
general configuration of the image generation system
using the image generation apparatus of the

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embodiment 3-1, and is a diagram showing a configuration example of the image generation system;

5　　Fig.63 is a schematic diagram showing a general configuration of the image generation system using the image generation apparatus of the embodiment 3-1, and is a diagram showing another configuration example of the image generation system;

10　　Fig.64 is a flow diagram showing processing of the virtual viewpoint image generation method of the embodiment 3-2;

Fig.65 is a schematic diagram for explaining other generation method in the image

15　generation method in the third embodiment;

Fig.66 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a flow diagram showing an example of the whole processing procedure;

20　　Fig.67 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a diagram showing an example of a method for setting the projection plane;

Fig.68 is a schematic diagram for

25　explaining the image generation method of the embodiment 4-1, and is a diagram showing an example of a method for setting the projection plane;

Fig.69 is a schematic diagram for explaining the image generation method of the

30　embodiment 4-1, and is a diagram for explaining a method for setting projection point series;

Fig.70 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a flow diagram showing an

35　example of processing procedure of steps for determining the color information and the existence probability of the projection point;

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Fig.71 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a diagram for explaining a method for determining the existence probability;

5   Fig.72 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a diagram for explaining a method for determining the existence probability;

Fig.73 is a schematic diagram for

10   explaining the image generation method of the embodiment 4-1, and is a diagram for explaining a method for determining the existence probability;

Fig.74 is a schematic diagram for explaining the image generation method of the

15   embodiment 4-1, and is a diagram for explaining a method for determining the existence probability;

Fig.75 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a diagram for explaining a

20   method for generating the two-dimensional images to be displayed on each image display plane;

Fig.76 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a diagram for explaining a

25   method for generating the two-dimensional images to be displayed on each image display plane;

Fig.77 is a schematic diagram for explaining the image generation method of the embodiment 4-1, and is a diagram for explaining a

30   method for generating the two-dimensional images to be displayed on each image display plane;

Fig.78 is a schematic diagram for explaining the image generation method of the embodiment 4-2, and is a diagram showing

35   relationship between the projection point and the corresponding point;

Fig.79 is a schematic diagram for

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explaining the image generation method of the
embodiment 4-2, and is a flow diagram showing an
example of steps for determining the color
information and the existence probability of the
5   projection point;

Fig.80 is a schematic diagram for
explaining the image generation method of the
embodiment 4-2, and is a diagram for explaining a
method for obtaining the existence probability;

10   Fig.81 is a schematic diagram for
explaining the image generation method of the
embodiment 4-2, and is a diagram for explaining a
method for obtaining the existence probability;

Fig.82 is a schematic diagram for
15   explaining an arbitrary viewpoint image generation
method of the embodiment 4-3, and is a flow diagram
showing an example of the whole processing
procedure;

Fig.83 is a schematic diagram for
20   explaining an arbitrary viewpoint image generation
method of the embodiment 4-3, and is a diagram for
explaining the principle of rendering;

Figs.84A and 84B are flow diagrams showing
processing procedure for converting the existence
25   probability to the transparency

Fig.85 is a schematic diagram showing a
general configuration of the image generation
apparatus of the embodiment 4-4;

Fig.86 is a schematic diagram showing a
30   general configuration of the image generation
apparatus of the embodiment 4-4;

Fig.87 is a schematic diagram showing a
general configuration of the image generation
apparatus of the embodiment 4-4, and is a diagram
35   showing a configuration example of the image
generation system using the image generation
apparatus;

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Fig.88 is a schematic diagram showing a general configuration of the image generation apparatus of the embodiment 4-4, and is a diagram showing a configuration example of the image

5   generation system using the image generation apparatus;

Fig.89 is a schematic diagram showing a general configuration of the image generation apparatus of the embodiment 4-4, and is a diagram

10   showing a configuration example of the image generation system using the image generation apparatus;

Fig.90 is a schematic diagram for explaining the three-dimensional image display

15   method of the embodiment 5-1 according to the fifth embodiment, and is a flow diagram showing an example of the whole processing procedure;

Fig.91 is a schematic diagram for explaining the three-dimensional image display

20   method of the embodiment 5-1, and is a diagram showing an example of a method for setting the projection plane;

Fig.92 is a schematic diagram for explaining the three-dimensional image display

25   method of the embodiment 5-1, and is a diagram showing an example of a method for setting the projection plane;

Fig.93 is a schematic diagram for explaining the three-dimensional image display

30   method of the embodiment 5-1, and is a diagram for explaining a method for setting projection points;

Fig.94 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-1, and is a flow diagram

35   showing an example of processing procedure of steps for determining the color information and the existence probability of the projection point;

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Fig.95 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-1, and is a diagram for explaining a method for determining the existence
5   probability;

Fig.96 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-1, and is a diagram for explaining a method for determining the existence
10 probability;

Fig.97 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-1, and is a diagram for explaining a method for determining the existence
15 probability;

Fig.98 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-1, and is a diagram for explaining a method for generating the two-
20 dimensional images to be displayed on each image display plane;

Fig.99 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-1, and is a diagram for
25 explaining a method for generating the two-dimensional images to be displayed on each image display plane;

Fig.100 is a schematic diagram for explaining the three-dimensional image display
30 method of the embodiment 5-1, and is a diagram for explaining a method for generating the two-dimensional images to be displayed on each image display plane;

Fig.101 is a schematic diagram for
35 explaining the three-dimensional image display method of the embodiment 5-2, and is a diagram showing relationship between the projection point

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and the corresponding point;

Fig.102 is a schematic diagram for explaining the three-dimensional image display method of the embodiment 5-2, and is a flow diagram
5   showing an example of steps for determining the color information and the existence probability of the projection point;

Fig.103 is a schematic diagram for explaining the three-dimensional image display
10 method of the embodiment 5-2, and is a diagram for explaining a method for obtaining the existence probability;

Fig.104 is a schematic diagram for explaining the three-dimensional image display
15 method of the embodiment 5-2, and is a diagram for explaining a method for obtaining the existence probability.

    [Explanation of symbols]
20 (First embodiment)
    1,1A,1B,1C … virtual viewpoint image generation apparatus, 101 … virtual viewpoint determination means, 102 … object image obtaining means, 103 … image generation means, 103a … projection plane
25 determination means, 103b … reference viewpoint determination means, 103c … texture array keeping means, 103d … corresponding point matching processing means, 103e … color information determination means, 103f … existence probability
30 information determination means, 103g … rendering means, 104 … generated image output means, 2 … viewpoint position input means, 3 … object taking means (camera), 4 … image display means, 6 … virtual viewpoint image, 7 … image of object, 7A … a part
35 where the image is deteriorated, 7B … a part where the image is lost
    (Second embodiment)

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6,6A,6B,6C … image generation apparatus, 601 …
object image obtaining means, 602 … observer
viewpoint setting means, 603 … projection plane
setting means, 604 … projection plane information
5　storing area keeping means, 605 … color
information/existence probability determination
means, 606 … projection plane information – display
plane information conversion means, 607 … image
output means, 7,7A,7B … image display means, 8,8A,8B
10　… object image taking means, 9,9A,9B … reference
viewpoint input means
　(Third embodiment)
2,2A,2B,2C … image generation apparatus, 201 …
object image obtaining means, 202 … virtual
15　viewpoint setting means, 203 … projection plane etc.
setting means, 204 … texture array keeping means,
205 … color information/existence probability
determination means, 206 … rendering means, 207 …
generated image output means, 3,3A,3B … object image
20　taking means, 4,4A,4B … viewpoint information input
means, 5,5A,5B … image display means, 6 … polarizing
binary optical system, 7,7A,7B … image sensor, 8 …
beam splitter, 9 … polarizing filter, 10 … variable
focus lens, 11a,11b,11c,11d … fixed focus lens, 12 …
25　lens holder
　(Fourth embodiment)
2,2A,2B,2C … image generation apparatus, 201 …
object image obtaining means, 202 … observer
viewpoint setting means, 203 … projection plane etc.
30　setting means, 204 … texture array keeping means,
205 … color information/existence probability
determination means, 206 … projection plane
information – display plane information conversion
means, 207 … image output means, 208 … rendering
35　means, 3,3A,3B … image display means, 4,4A,4B …
object image taking means, 5,5A,5B … reference
viewpoint information input means

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(Fifth embodiment)
2,2A,2B,2C … three-dimensional image generation apparatus, 201 … object image obtaining means, 202 … observer viewpoint setting means, 203 … projection
5 plane etc. setting means, 204 … texture array keeping means, 205 … color information/existence probability determination means, 206 … projection plane information - display plane information conversion means, 207 … image output means, 3,3A,3B
10 … image display means, 4,4A,4B … object image taking means, 5,5A,5B … reference viewpoint input means

PREFERRED EMBODIMENTS FOR CARRYING OUT THE INVENTION

In the following, first to fifth
15 embodiments are described as the preferred embodiments for carrying out the invention.

[First embodiment]

First, the first embodiment of the present invention is described.   The first embodiment
20 mainly corresponds to claims 1-11. In this embodiment, although three primary colors of red (R), green (G) and blue (B) are used for representing color information as an example, other representation such as brightness (Y) or color
25 difference (U, V) can be used. In addition, for black-and-white images, only brightness information can be used as the color information. In figures for explaining the first embodiment, the same reference signs are assigned for the same functions.
30   Before explaining each embodiment of the first embodiment, principle of a virtual viewpoint image generation method of the first embodiment is described.
       Figs.2-5 are schematic diagrams for
35 explaining the principle of the virtual viewpoint image generation method of the present invention. Fig.2 shows examples of projection plane group,

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camera, reference viewpoint, projection point and corresponding point. Fig.3A and Fig.3B show examples of graphs of correlation degree between corresponding points. Fig.4A shows an example of
5 mixing processing according to the transparency of projection points, and Fig.4B represents mixing processing for color information according to transparency in a color space. Fig.5 shows examples of an object, a projection plane group, a reference
10 viewpoint, a virtual viewpoint and a projection point.

   The method for generating the virtual viewpoint image in this invention includes: a step 1 of setting the projection plane group having the
15 multi-layered structure; a step 2 of obtaining points (corresponding points), on plural images taken by the camera, corresponding to each point (projection point) on the projection planes; a step 3 of mixing color information of the plural
20 corresponding points or selecting one of them to determine color information of the projection point; a step 4 of calculating, based on correlation degrees of the corresponding points or the adjacent regions, degree (existence probability information)
25 of probability that the object exists at the distance of the projection point for each of the plural projection points overlapping when viewed from a viewpoint (reference viewpoint) in a space; a step 5 of performing mixing processing on the color
30 information of reference points overlapping when viewed from the virtual viewpoint according to the existence probability information so as to determine color information of each pixel in the virtual viewpoint; and a step 6 of repeating the steps 1-5
35 for every point corresponding to pixels of virtual viewpoint image. That is, the method of the present invention does not intend to obtain a geometrical

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object model accurate for every case and every
portions like the conventional method. But,
assuming that an estimated value having adequate
reliability cannot be obtained in the distance
5　estimation depending on picture-taking conditions
and portions of the object, a portion, by which an
estimated value of low reliability is obtained, is
drawn vaguely so as to provide the portion with low
contribution to image generation for avoiding
10　extreme image deterioration, and a portion, by which
distance data of high reliability is obtained, is
drawn clearly so as to provide the portion with high
contribution to image generation.

　　　　　The reliability of estimation is
15　determined in the following way according to the
degree of correlation (correlation degree) of
corresponding points of the taken images. For
example, as shown in Fig.2, a reference viewpoint R,
center positions $C_i(i=1,2,\ldots,N)$ of the camera, and
20　projection planes $L_j(j=1,2,\ldots,M)$ that are parallel
each other are set, and it is assumed that a
corresponding point obtained by taking a projection
point T_j by a camera at a center position C_i is G_{ij} .

　　　　　As a result, for example, a set
25　$\{G_{im}|i=1,2,\ldots,N\}$ of corresponding points with respect
to a projection point T_m on a projection plane L_m is
obtained, and the degree of correlation (correlation
degree) of them can be calculated.

　　　　　A graph shown in Fig.3A or Fig.3B can be
30　obtained by calculating the correlation degrees for
plural projection points $T_j(j=1,2,\ldots,M)$ that lie on a
straight line when viewed from the reference
viewpoint R, and by indicating the distance l
between the reference viewpoint R and the projection
35　plane using the lateral axis, and indicating the
correlation degree using the horizontal axis. A
concrete calculation method of the correlation

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degree is described in later-described embodiments.
Here, the graph is shown assuming that the larger
the correlation degree is, the larger the degree of
the correlation among correspondence points is.

5   At a distance corresponding to high
correlation degree, corresponding points in plural
cameras are similar so that there is a high
possibility that the same point of the object is
taken at the position of the projection point by the
10   cameras. Therefore, there is a high possibility
that the object exists at the distance. When only
one distance by which the object exits on the line
passing through the reference viewpoint R exists, it
can be estimated that the object exists at a
15   distance $l=l^*$ corresponding to the highest
correlation degree as shown in Fig.3A and Fig.3B

     At this time, as shown in Fig.3A, when the
correlation degree of the corresponding points at
the distance $l=l^*$ is far higher than other
20   candidates, highly reliable estimation can be
performed. However, as shown in Fig.3B, when there
are plural candidates of estimation values such as
the distance $l=l^*$ and distance $l=l'$ and when the
correlation degrees of the corresponding points are
25   almost the same, the reliability of the estimation
becomes low.

     In the case shown in Fig.3B, when a method
for rendering only one projection point
corresponding to the distance $l=l^*$ of the highest
30   correlation degree is adopted, large noise appears
on a generated image if the object actually exists
at the distance $l=l'$ due to estimation error.

     On the other hand, according to the
present invention, a probability (existence
35   probability information) that the object exists is
calculated based on the correlation degree, so that
plural projection points are rendered with clarity

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according to the existence probability information.
As a result, plural projection points are rendered
vaguely when the estimation reliability is low, so
that there is an effect that noise is inconspicuous
5   on the generated image and an image looks better for
the observer can be generated.

On the other hand, a projection point
corresponding to high existence probability is
clearly rendered when the estimation reliability is
10   high, so that a better image can be generated.

In addition, the rendering method of
this invention can be simply implemented using
texture-mapping that is a basic method in computer
graphics, so that there is an effect that computing
15   workload can be decreased such that even three-
dimensional graphics hardware mounted on a popular
personal computer can perform rendering processing
nicely.

In addition, in the virtual viewpoint
20   image generation method of this invention, each
reference point on the projection plane has
transparency with a gradation from transparent to
opaque, and the transparency in each reference point
is calculated by converting the existence
25   probability information obtained by the step 4. In
step 5, the mixing processing for obtaining color
information of each point in the virtual viewpoint
is successively performed from a projection point
far from the virtual viewpoint to a projection point
30   near to the virtual viewpoint. Color information
obtained by the mixing processing up to a projection
point is obtained by internally dividing, with a
ratio according to transparency, between color
information at the projection point and color
35   information obtained by mixing processing up to a
previous projection point. The color information
obtained by the mixing processing is an internal

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division of color information at a stage and next color information.

For example, as shown in Fig.4A, considering a case in which projection planes
5   L_j(j=1,2,…,M), projection points T_j(j=1,2,…,M) and vectors K_j(j=1,2,…,M) having elements of red, green and blue (R,G,B) and indicating color information are set in a color space represented by the following equation 1.
10   [Equation 1]

$$K_j \in V, V \equiv \left\{ (R,G,B) \middle| 0 \le R \le 1, 0 \le G \le 1, 0 \le B \le 1 \right\}$$

In addition, it is assumed that transparency α_j(j=1,2,…,M) of the projection point is set as
15   shown in the following equation 2.

[Equation 2]

$$0 \le \alpha_j \le 1$$

At this time, color information D_m obtained by mixing processing up to j=m can be represented as
20   recurrence formulas shown in the following equation 3 and equation 4, color information D_M obtained by performing mixing processing up to j=M that is nearest to the virtual viewpoint becomes color information at the virtual viewpoint.
25   [Equation 3]

$$D_m = \alpha_m K_m + \left(1 - \alpha_m \right) D_{m-1}$$

[Equation 4]

$$D_1 = \alpha_1 K_1$$

At this time, as represented by the relationship of
30   the equation 2 and the equation 3, the color information D_m is an internally divided point between K_m and D_{m-1} in a color space V. Thus, as shown in Fig.4B, when $K_m, D_{m-1} \in V$ is satisfied, $D_m \in V$

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holds true.

Then, if conditions of the equation 1 and the equation 2 are satisfied, it is ensured that the following equation 5 holds true with respect to the color information D_M in the virtual viewpoint.

[Equation 5]

$$D_M \in V$$

The equation 5 can be proved using mathematical induction, but detailed description is not provided here.

That is, by setting the color information and the transparency at the projection point such that the equations 1 and 2 are satisfied, the color information of the virtual viewpoint can be limited within a proper color space v without fail.

According to the above-mentioned features, when plural virtual viewpoint images for the same object are generated, even when color information and transparency of projection points are calculated from one reference viewpoint, if the color information and the transparency satisfy the equation 1 and the equation 2, images can be generated with proper color information bounds for all virtual viewpoint images.

For example, as shown in Fig.5, a case is considered in which, when an object Obj exists, and two projection planes L_1 and L_2, a reference viewpoint R and a virtual viewpoint P are set, pieces of color information of projection points T_1, T_2, T_1', T_2' are K_1, K_2, K_1', K_2' respectively, and degrees of probability of existence of object are $\beta_1, \beta_2, \beta_1', \beta_2'$ respectively.

The degree (existence probability information) of probability of existence of the object is calculated on a line passing through the virtual viewpoint R, and a sum of existence

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probability information at projection points on the
same straight line is 1. Since the surface of the
object exists near the projection points T_1' and T_2,
existence probability information at the points are
5 higher than those of T_1 and T_2'. Then, the
existence probability information is represented by
the following equations 6 and 7.

[Equation 6]

$$\beta_1 \cong 0, \quad \beta_2 \cong 1$$

10   [Equation 7]

$$\beta_1' \cong 1, \quad \beta_2' \cong 0$$

At this time, color information K_A at a
point A of the image plane of the virtual viewpoint
P can be calculated by assigning weights to color
15 information of projection points on the line PA and
adding the weighted color information of the
projection points as represented by the following
equation 8.

[Equation 8]

20
$$K_A = \beta_1' K_1' + \beta_2 K_2$$

The equation 8 can be represented as the following
equation 9 according to the equations 6 and 7.

[Equation 9]

$$K_A \fallingdotseq K_1' + K_2$$

25 When being viewed from the virtual viewpoint P, T_A'
is blocked by T_A. Therefore, brightness of each
component of (R,G,B) is increased by K_1' as shown in
the equation 9 although actual color information at
the point A is $K_A=K_2$.

30   In addition, when each component of K_A and
K_A' has large brightness, K_A exceeds effective region
of the color space. Therefore, clipping processing
becomes necessary for K_A to fall within a

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predetermined limit.

Accordingly, for example, results shown in
equations 10 and 11 are obtained by calculating
transparency from existence probability information
5   using a calculation method described in an after-
mentioned example 1-2.

[Equation 10]

$$\alpha_2 = \beta_2, \quad \alpha_1 = 1$$

[Equation 11]

10
$$\alpha_2' = \beta_2', \quad \alpha_1' = 1$$

In the equation 10 and the equation 11, each of α_1,
α_2, α_1' and α_2' is transparency at T_1, T_2, T_1' and T_2'
respectively.

For obtaining color information of each
15 point with respect to the virtual viewpoint, mixing
processing is performed successively from a
projection point far from the virtual viewpoint
toward a projection point near the projection point,
and color information obtained by mixing processing
20 up to a projection point is obtained by performing
interior division between color information at the
projection point and color information obtained by
mixing processing up to a previous projection point
at a ratio of transparencies, so that K_A is
25 represented by the following equation 12.

[Equation 12]

$$K_A = \alpha_2 K_2 + \left(1 - \alpha_2\right) \alpha_1' K_1'$$

The equation 12 can be represented as the following
equation 13 according to the equation 6, the
30 equation 7, the equation 10 and the equation 11.
The equation 13 represents good approximation of
actual color information.

[Equation 13]

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$$K_A \doteqdot K_2$$

As mentioned above, when performing image generation using the existence probability information as it is, there is no problem if the reference viewpoint and the virtual viewpoint are the same. But, when they are different, brightness may increase near blocked region. On the other hand, according to image generation in which the existence probability information is changed to transparency, the above mentioned phenomenon can be prevented.

In addition, when the reference viewpoint and the virtual viewpoint are different in the image generation using the existence probability information as it is, there is no guarantee that color information that is calculated using after-mentioned equations falls within an effective color information limit, and correction processing is necessary, for example. On the other hand, according to the image generation in which the existence probability information is converted to the transparency, such correction is not necessary.

In addition, according to the image generation in which the existence probability information is converted to transparency, a semitransparent object can be efficiently represented, so that there is an effect that the present invention can be applied more widely to more objects in the actual world.

In addition, according to the virtual viewpoint image generation method, a group of projection planes specific for each camera is set in step 1. In step 3, as to color information of a projection point, color information of corresponding point of an image taken by a camera specific for a projection plane to which the projection point belongs is used. In step 4, the existence

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probability information is calculated using a
viewpoint of the camera, as the reference viewpoint,
specific to the projection plane to which the
projection point belongs. In mixing processing of
5   color information of the virtual viewpoint in step 5,
correction is performed according to position
relationship between the virtual viewpoint and each
reference viewpoint. Accordingly, since the group
of the projection planes specific to each camera is
10   set irrespective of position relationship among
cameras, even if placement of the cameras is
complicated or random, processing for setting the
group of the projection planes is not affected so
that image generation can be performed by consistent
15   processing method.

When the group of the projection planes
specific to each camera is set, mixing processing
between images taken by corresponding cameras is not
necessary as to color information of the projection
20   plane. Accordingly, for example, parallel
processing can be performed when using a computer,
so that the speed for generating the image can be
increased.

In addition, since all pieces of color
25   information of the group of the projection planes
associated with the same camera are the same, a
texture memory for storing the color information can
be shared when performing processing by a computer.
Therefore, even if the number of projection planes
30   is large, the memory is not consumed very much, so
that workload in the apparatus used for image
generation can be decreased.

In addition, since the camera
corresponding to a projection plane is uniquely
35   determined, calibration such as correction of
distortion of a lens can be performed easily and at
high speed by setting corresponding relationship of

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coordinates of them.

Therefore, a program that causes a specific apparatus or a widespread personal computer or the like to perform the virtual viewpoint image
5   generation method of the first embodiment of the present invention has wide application ranges and high versatility.

In the following, an apparatus for performing the virtual viewpoint image generation
10   method of the first embodiment and a concrete image generation method are described by taking examples.

(Embodiment 1-1)

Figs.6 and 7 are a schematic diagram showing an outline configuration of a virtual
15   viewpoint image generation apparatus of the embodiment 1-1 of the present invention. Fig.6 is a block diagram showing a configuration of the inside of an image generation apparatus, and Fig.7 is a configuration example of a system using the image
20   generation apparatus.

In Fig.6, 1 indicates a virtual viewpoint image generation apparatus, 101 indicates a virtual viewpoint determination means, 102 indicates an object image obtaining means, 103 indicates an image
25   generation means, 103a indicates a projection plane determination means, 103b indicates a reference viewpoint determination means, 103c indicates a texture array keeping means, 103d indicates a corresponding point matching processing means, 103e
30   indicates a color information determination means, 103f indicates an existence probability information determination means, 103g indicates a rendering means, 104 indicates a generated image output means, 2 indicates a viewpoint position input means, 3
35   indicates an object taking means, 4 indicates an image display means. In addition, in Fig.7, "User" indicates a user of the virtual viewpoint image

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generation apparatus, and "Obj" indicates an object.
As shown in Figs.6 and 7, the virtual
viewpoint image generation apparatus 1 of the
embodiment 1-1 includes the virtual viewpoint
5   determination means 101 for determining parameters
of a viewpoint (virtual viewpoint) input by using
the viewpoint position input means 2 by the user
"User", the object image obtaining means 102 for
obtaining images of the object Obj taken by the
10   object taking means (camera) 3, an image generation
means 103 for generating, based on the obtained
images of the object Obj, an image (virtual
viewpoint image) of the object Obj viewed from the
virtual viewpoint, and the generated image output
15   means 104 for displaying the virtual viewpoint image
generated by the image generation means 103 on the
image display means 4.
The virtual viewpoint determination means
101 determines position, direction and angle of view,
20   for example, as the parameters of the virtual
viewpoint. The viewpoint position input means 2 may
be a device such as a mouse for performing selection
based on operation of the user User, for example as
shown in Fig.7, or a device such as a keyboard by
25   which the user User directly inputs numerals, or may
be a position/posture detection sensor mounted by
the user User. In addition, the means may be
provided by other program or a program provided via
a network.
30   The object image obtaining means 102 can
successively obtain the position/posture of the
object that changes every moment at predetermined
intervals, for example, at 30Hz, and also can obtain
a still image of the object at any time, and also
35   can obtain the image by reading out the object image
taken beforehand from a recording apparatus. By the
way, it is desirable that the object images viewed

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from the plural viewpoint positions are taken at the
same time by synchronizing all cameras. But, this
condition is not necessary if changes of the
position and the posture of the object are
5 sufficiently slow so that the object can be regarded
as a still object.
        As shown in Fig.6, the image generation
means 103 includes projection plane determination
means 103a for determining positions and shapes of
10 the projection planes used·for image generation, the
reference viewpoint determination means 103b for
determining the position of the reference viewpoint,
the texture array keeping means 103c for assigning
an array of texture images, to be mapped to the
15 projection planes, to the memory, the corresponding
point matching processing means 103d for associating,
with each other, parts where the same region of the
object appears in the images of the object obtained
by the object image obtaining means 102 of plural
20 viewpoint positions, the color information
determination means 103e for determining color
information in the texture array kept by the
texture array keeping means 103c by performing
mixing processing on color information of the
25 obtained plural images of the object, the existence
probability information determination means 103f for
determining degrees (existence probability
information) of probability that the object exists
on the projection planes in the texture array kept
30 by the texture array keeping means 103c based on the
result of the corresponding point matching
processing means 103d, and the rendering means 103g
for rendering the projection planes viewed from the
virtual viewpoint based on the color information
35 determined by the color information determining
means 103e and the existence probability information
determined by the existence probability information

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determining means 103f.

The array kept in the texture array keeping means 103c includes color information and existence probability information of each pixel, in
5 which three primary colors of red (R), green (G) and blue (B), and the existence probability information are represented by 8 bits respectively, for example. However, the present invention is not dependent on such particular data representing format.

10 The image display means 4 is a display apparatus such as CRT (Cathode Ray Tube), LCD (Liquid Crystal Display) and PDP (Plasma Display Panel) connected to the generated image output means 104. The image display means 4 may be a display
15 apparatus of a two-dimensional plane shape, or may be a display apparatus having a curved surface surrounding the user User. When a display apparatus that can display a three-dimensional shape is used as the image display means 4, the virtual viewpoint
20 determination means 101 determines two virtual viewpoints corresponding to the user's right and left eyes and the image generation means 103 generates virtual viewpoint images viewed from the two virtual viewpoints so that independent images
25 can be provided to the right and left eyes of the user. In addition, by generating images viewed from more than two virtual viewpoints and using a three-dimensional display that can display images having more than two parallaxes, the three-dimensional
30 image can be provided to equal to or more than one users.

In addition, the system using the virtual viewpoint image generation apparatus 1 has a configuration shown in Fig.7, for example. When the
35 user User specifies desired viewpoint position / direction / image angle to the virtual viewpoint image generation apparatus 1 via the virtual

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position input means 2, the virtual viewpoint image
generation apparatus 1 photographs the object Obj
with the object taking means (cameras) 3 so as to
obtain the images. After that, the virtual

5   viewpoint image generation apparatus 1 generates an
image (virtual viewpoint image) from the specified
viewpoint based on the obtained images of the object.
The obtained virtual viewpoint image is presented to
the user User using the image display means 4.

10   The system configuration shown in Fig.7
shows an implementation example of the image
generation apparatus in the present invention. The
claims of the present invention are not limited to
such configuration, and positions, shapes and

15   implementation of each apparatus can be freely
determined within the scope of the present invention.
        In the following, before describing
concrete processing procedure of the image
generation processing by the image generation means

20   103, a mathematical principle model on which the
processing is based is described.
        Figs.8 and 9 are schematic diagrams for
explaining the mathematical principle model of the
virtual viewpoint image generation method using the

25   virtual viewpoint image generation apparatus of this
embodiment 1-1. Fig.8 shows an example of
projection conversion, and Figs.9 show an example of
coordinates conversion.
        In the image generation processing using

30   the virtual viewpoint image generation apparatus of
this embodiment 1-1, as shown in Fig.8, for example,
center positions $C_i(i=1,2,…,N)$ of the cameras 3, a
virtual viewpoint P and projection planes
$L_j(j=1,2,…,M)$ are set. In the following, it is

35   assumed that the center position C_i of the camera
indicates the camera itself in order to identify the
plural cameras 3, and that, in the same way, P

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indicates the virtual viewpoint itself and indicates the center position of the virtual viewpoint.

Although the cameras C_i are placed in a lateral line in Fig.8, the present invention is not

5   limited to such placement. For example, various placements such as two-dimensional lattice, arc-shape and the like can be applied. In addition, the placement of the projection planes L_j are not necessarily parallel. Curved planes can be used as

10 described later in the embodiment 1-3. However, in the descriptions of this embodiment 1-1, the projection planes L_j are plane.

In the virtual viewpoint image generation method of the present embodiment, in order to

15 generate an image of the virtual viewpoint P at which the camera is not placed actually based on the images of the object Obj obtained at the points at which the cameras are actually placed, a procedure is basically adopted in which a part of the image of

20 the object taken by the camera C_i is texture-mapped on the projection plane L_j that is assumed to exist in the virtual viewpoint image generation apparatus 1 such as a computer, then, an image obtained by viewing the texture-mapped projection planes from

25 the virtual viewpoint P is generated by coordinate calculation processing.

When performing such processing, each of three-dimensional points of the virtual viewpoint P and the cameras C_i is projected to a two-dimensional

30 point of each image plane.

Generally, a matrix for projecting a point (X,Y,Z) in a three-dimensional space to a point (x,y) in an image plane is a matrix having three rows and four columns, and can be represented by the

35 following equation 14 and the equation 15.

[Equation 14]

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$$s\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \Phi \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

[Equation 15]

$$\Phi = \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} \end{bmatrix}$$

In this case, for example, a matrix Φ_0 representing
5　perspective projection conversion of focal length f
in which the original point is the center is as
shown in the following equation 16.

[Equation 16]

$$\Phi_0 = \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

10　An image dealt by the computer is a so-called
digital image, and is represented by a two-
dimensional array in a memory. The coordinate
system (u,v) representing the positions of the array
is called a digital image coordinate system.
15　　　At this time, for example, one point on a
digital image having a size of 640 pixels × 480
pixels can be represented by a variable u that takes
one of integers from 0 to 639 and a variable v that
takes one of integers from 0 to 479, and color
20　information at the point is represented by data
obtained by quantizing red (R), green (G) and blue
(B) information at the address with 8 bits, for
example.

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In addition, at this time, the image coordinates (x,y) shown in Fig.9A are associated with the digital image coordinates (u,v) shown in Fig.9B in an one-to-one correspondence manner, and
5   they have the following relationship shows in the equation 17.

[Equation 17]

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} k_u & -k_u \cot\theta & u_0 \\ 0 & k_v/\sin\theta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

The x axis shown in Fig.9A is parallel to
10   the u axis shown in Fig.9B, and it is assumed that unit lengths for the u axis and the v axis are k_u and k_v respectively, and an angle between the u axis and the v axis is θ.

Although the digital image coordinates (u,
15   v) take discrete values when writing into or reading out the two-dimensional array, it is assumed that the coordinates take continuous values unless otherwise specified in the following descriptions, and that proper discretization processing is
20   performed when accessing the array.

In addition to the coordinate conversion shown in the relationship of the equation 17, conversion for correcting distortion by aberration of the lens can be performed.
25   In the following, a concrete procedure for generating the virtual viewpoint image is described using the mathematical principle model.

Figs.10-17 are schematic diagrams for explaining the generation processing procedure for
30   the virtual viewpoint image of this embodiment 1-1. Fig.10 is a flow diagram showing the whole generation processing. Fig.11 shows a concrete flow diagram showing steps for generating the virtual

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viewpoint image. Fig.12 shows an example of a
setting method of the projection planes. Fig.13
shows examples of projection points, projection
point series and a set of projection point series.

5   Fig.14 shows examples of a reference viewpoint,
projection points and angles based on various camera
positions for explaining mixing processing of color
information. Fig.15 shows an example of
corresponding point matching processing. Fig.16 is

10 a figure for explaining rendering processing.
Fig.17 shows an example of a generated virtual
viewpoint image.

   As shown in Fig.10, when generating the
virtual viewpoint image using the virtual viewpoint

15 image generation apparatus 1, first, the virtual
viewpoint determination means determines the
parameters of the virtual viewpoint P based on a
request from the user User (step 501). In the step
501, the position, the direction and image angle and

20 the like are determined, for example.
   Next, image of the object obj taken by the
cameras 3 (C_i) are obtained by the object image
obtaining means 102 (step 502).
   Next, based on images of the object

25 obtained by the object image obtaining means 102, an
image (virtual viewpoint image) of the object Obj
viewed from the virtual viewpoint P is generated
(step 503).
   In the step 503, for example, processing

30 of each step shown in Fig.11 is performed so that
the virtual viewpoint image is generated.
   In the processing in step 503, the
projection plane determination means 103a determines
the position and the shape of the projection planes

35 L_j ($j \in J, J \equiv \{1,2,…,M\}$) of multiple-layered structure
used for generating the virtual viewpoint image
(step 503a). When setting the projection planes L_j

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in the step 503a, projection planes having plane
shape are placed in parallel at the same intervals
as shown in Fig.8, for example.

5   When the cameras C_i are arranged at the
same intervals, the planes (projection planes) can
be arranged at a series $l_d(d=1,2,3,…)$ of distances
obtained by the following equation 18, wherein the
placement interval of the camera is B, focal length
of the camera is F, and the size of one pixel on the
10   image is δ.

[Equation 18]

$$l_d = \frac{BF}{\delta d} \quad (d = 1, 2, 3, \cdots)$$

In this case, depth resolution of corresponding
point matching among cameras is the same as the
15   placement interval of the projection planes. That
is, as shown in Fig.12, assuming that cameras C_n and
C_{n-1} are placed at an interval B, a point of the
camera C_n on the image plane is A, a point
corresponding to the point A in C_n on the image
20   plane of the camera C_{n-1} is A_0', and that a point of
d-th pixels from A_0' is A_d', corresponding points of
the point A is a series of $\{A_0' | d=1,2,…\}$ and series
of distances calculated in this case are provided by
the equation 18.

25   The setting example of the projection
planes L_j is one example, and it is basically
sufficient to set more than one different projection
planes in the image generation method of the present
invention. The present invention is not limited to
30   such particular setting method of the projection
planes.

When the processing in step 503a ends,
next, the reference viewpoint determination means
103b determines a reference point (reference
35   viewpoint) R used for calculating the degree

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(existence probability information) of probability
of existence of the object on the projection point
(step 503b). The position of the reference
viewpoint R may be the same as the position of the
5   virtual viewpoint P, or, when there are plural
virtual viewpoints, the position of the reference
viewpoint R may be a barycenter position of the
plural virtual viewpoints. But, the present
invention does not provide a method dependent on how
10 to decide a particular reference viewpoint.

After performing the processing of the
step 503b, next, many projection points are set on
the projection planes (step 503c). At this time,
the projection points are set such that the
15 projection points exist on plural lines that pass
through the reference viewpoint R, so that
projection points existing on the same line are
dealt with together as a projection point series.
For example, as shown in Fig.13, focusing attention
20 on a line that passes through the reference
viewpoint R, and assuming that a projection point of
a projection plane L_j is T_j and that a projection
point series of the projection points is S, S can be
represented as $S=\{T_j | j \in J\}$. In addition, assuming
25 that a set of projection point series is Σ, $S \in \Sigma$
holds true.

After completing the processing of the
step 503, next, the texture array keeping means 103c
keeps, on the memory of the image generation
30 apparatus, the array (texture array) for storing the
images that are to be texture-mapped on the
projection planes (step 503d). At this time, the
array to be kept includes color information and
existence probability information by 8 bits for each
35 pixel as texture information corresponding to the
position of the projection point.

In the step 503d, correspondence between

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the two-dimensional digital coordinates (U_j, V_j) of the pixel of the texture array and the three-dimensional coordinates (X_j, Y_j, Z_j) of the projection point T_j is also set. At this time, for example,

5   values of (X_j, Y_j, Z_j) for every (U_j, V_j) may be set as a table. Or, only some values of (X_j, Y_j, Z_j) of representative (U_j, V_j) may be set and other correspondences are obtained by interpolation processing (linear interpolation, for example).

10   After completing the processing of the step 503d, color information and existence probability information for each pixel corresponding to each projection point kept in the step 503d are determined based on the images of the object

15   obtained in the step 502. At that time, the projection point series S are scanned successively within a limit of $S \in \Sigma$. Further, projection points T_j are scanned successively within a limit of $T_j \in S$, so that double loop processing is performed.

20   In the loop processing, the projection point series S to be operated is initialized to a start position (step 503e). Then, next, the projection point T_j is initialized to a start position in the projection point series S, for

25   example, initialized to $j=1$ (step 503f).

After finishing the step 503e and the step 503f, coordinates (X_j^*, Y_j^*, Z_j^*) of the projection point T_j is obtained, and each position on each image plane corresponding to the point at the

30   position (X_j^*, Y_j^*, Z_j^*), when taking the point at the position (X_j^*, Y_j^*, Z_j^*) by each camera, is calculated using relationships from the equation 14 to the equation 17 (step 503g). At this time, a set of cameras for which the corresponding points are

35   calculated is represented as $\Xi \equiv \{C_i | i \in I\}$. The set Ξ of the cameras may be all cameras, or may be one or plural cameras selected from the cameras

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according to positions of the virtual viewpoint P,
the reference viewpoint R and projection points T_j.

Assuming that corresponding points of each
camera obtained here are G_{ij} ($i \in I$), and that the
5   digital coordinates are represented by (u_{ij}^*, v_{ij}^*) ($i \in I$).

After completing the processing in step
503g, next, the color information determination
means 103e determines color information on a pixel
10   (U_j^*, V_j^*) on the texture array corresponding to the
projection point T_j by mixing color information in
(u_{ij}^*, v_{ij}^*) ($i \in I$) (step 503h). The mixing processing
is to calculate an average of pieces of color
information of corresponding points of each camera,
15   for example.

In addition, in the mixing processing, it
is possible to assign weights according to an angle
θ_{ij} formed by the camera C_i, the projection point T_j
and the reference viewpoint R. For example, as
20   shown in Fig.14, assuming that the set of camera is
$\Xi = \{C_n, C_{n+1}, C_{n+2}\}$ ($I=\{n, n+1, n+2\}$). In this case,
assuming that vectors representing color information
(R, G, B) at the projection point T_j and the
corresponding point G_{ij} are expressed by K_j and K_{ij}
25   respectively. When K_j is determined by the
following equation 19, for example, the smaller the
angle between the line from the reference viewpoint
R to the projection point T_j and the line of sight
of the camera is, the greater the degree
30   contributing to the mixing processing is.
[Equation 19]

$$K_j = \frac{\sum_{i \in I} \cos \theta_{ij} \cdot K_{ij}}{\sum_{i \in I} \cos \theta_{ij}}$$

After completing the processing in step 503h, the

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corresponding point matching processing means 103d calculates the degree Q_j of correlation of the corresponding points $G_{ij}(i \in I)$ of each camera with respect to the projection point T_j (step 503i).

5　When using the following equation 20, the degree Q_j of correlation becomes a positive value, and the higher the correlation of the corresponding points, the smaller the Q_j is.

[Equation 20]

$$Q_j = \sum_{i \in I} \left(K_j - K_{ij}\right)^2$$

10

In the equation 20, although color information of the projection point and color information of the corresponding point are compared at only one point, comparison of color information may be performed

15　between plural points near the projection point and plural points near the corresponding point. At this time, for example, as shown in Fig.14, when defining a region Φ_j near the projection plane T_j and a corresponding region Ψ_{ij} at the camera C_i, degree Q_j

20　of correlation of the regions can be calculated by the following equation 21, for example.

[Equation 21]

$$Q_j = \sum_{i \in I} \sum_{\substack{(U_j, V_j) \in \Phi_j \\ (u_{ij}, v_{ij}) \in \Psi_{ij}}} \left\{K\left(U_j, V_j\right) - K\left(u_{ij}, v_{ij}\right)\right\}^2$$

wherein $K(U_j, V_j)$ indicates an estimated value of

25　color information at the coordinates (U_j, V_j) in the texture array and $K(u_{ij}, v_{ij})$ indicates color information at coordinates (u_j, v_j) in a photographed image by the camera C_i.

The method for calculating the degree of

30　correlation is not limited to the above-mentioned one, and the present invention is not dependent on a particular calculation method. For example, in the

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example shown in Fig.15, the region Φ_j is formed by 8 pixels including the pixel of the projection point T_j and surrounding pixels, and the corresponding region Ψ_{ij} is formed by 8 pixels including the pixel

5   of the corresponding point and surrounding pixels. However, the defining method for the near region Φ_j and the corresponding region Ψ_{ij} is not limited to this example.

After completing the processing of the

10   step 503i, the projection point T_j is updated (step 503j), and it is determined whether every projection point $T_j \in S$ is scanned (step 503k). If all points are scanned, the step proceeds to the step 503l. If all points are not scanned, the step returns to the

15   step 503g.

When it is determined that all points have been scanned in step 503k, next, the existence probability information determination means 103f determines, based on the degree Q_j of correlation

20   calculated in step 503i, degree (existence probability information) β_j of probability of existence of the object on the projection point with respect to every projection point $T_j (j \in J)$ on the line that passes through the reference viewpoint R

25   (step 503l). In the determination, the existence probability information β_j needs to satisfy the conditions of the equation 22 and the equation 23.
[Equation 22]

$$0 \le \beta_j \le 1$$

30   [Equation 23]

$$\sum_{j=1}^{M} \beta_j = 1$$

Further, the higher the probability of existence of the object at the projection point T_j is, the nearer

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to 1 the probability is. Therefore, the existence
probability information β_j ($j \in J$) is obtained by
performing conversion processing represented by the
following equation 24 and the equation 25 on the
5   degree Q_j of correlation between the projection
point and the corresponding points calculated in the
step 503i, for example.

[Equation 24]

$$\widetilde{\beta}_j = \frac{1}{Q_j}$$

10   [Equation 25]

$$\beta_j = \frac{\beta_j}{\sum_{j=1}^{M} \widetilde{\beta}_j}$$

However, since the existence probability information
β_j only needs to satisfy the conditions of the
equation 22 and the equation 23, the conversion
15   processing is not necessarily limited to the method
represented by the equation 24 and the equation 25.
After completing the processing of the
step 503l, next, the projection point series S is
updated (step 503m), and it is determined whether
20   all projection point series $S \in \Sigma$ are scanned (step
503n). If all projection point series are scanned,
the step proceeds to the next step 503o. If all
projection point series are not scanned, the step
returns back to step 503f.
25   If it is determined that all projection
point series are scanned in step 503n, next, the
rendering means 103g renders and generates an image
obtained by viewing the projection planes
L_j ($j=1,2,\ldots,M$) having multi-layered structure from
30   the virtual viewpoint P according to the existence

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probability information β_j (step 503o). For example, as shown in Fig.16, assuming that coordinates of the virtual viewpoint P on the image are represented as (u_p, v_p). At this time, color information K_p^* of a

5 pixel $p^*(u_p^*, v_p^*)$ on the image is determined by multiplying color information $\{K_j^* | j \in J\}$ of projection point series $\{T_j^* | j \in J\}$ on the line connecting p and p^* with existence probability information $\{\beta_j^* | j \in J\}$ and by adding the multiplied

10 color information, so that the color information K_p^* is represented by the following equation 26.

[Equation 26]

$$K_P^{*} = \sum_{j=1}^{M} \beta_j^{*} K_j^{*}$$

By determining color information for every pixel on

15 the image plane, the image for the virtual viewpoint P is obtained.

In addition, instead of using the equation 26, by calculating K_p^* using the following equation 27, it is guaranteed that K_p^* is within an effective

20 color space even when the reference viewpoint R and the virtual viewpoint P are different.

[Equation 27]

$$K_P^{*} = \frac{\displaystyle\sum_{j=1}^{M} \beta_j^{*} K_j^{*}}{\displaystyle\sum_{j=1}^{M} \beta_j^{*}}$$

Although a procedure in which color information is

25 determined by scanning the pixels on the image plane is shown, it is not limited to the procedure. For example, rendering processing can be relied on general graphic library such as OpenGL, DirectX and

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the like by passing data such as configuration of projection planes, texture array and setting of viewpoint P and the like to the graphic library.

5   Then, generation processing (step 503) of the virtual viewpoint image ends, so that the generated virtual viewpoint image is displayed on the image display means 4 (step 504). As shown in Fig.17, for example, in the virtual viewpoint image 6 displayed on the image display means 4, a portion

10   7A in which the degree Q_j of the correlation calculated in step 5031 is low, that is, in which reliability of estimation value is low, is rendered obscurely and appears blurred in the image 7 of the object. Therefore, for example, a part does not

15   appear to lack like the conventional virtual viewpoint image 6 as shown in Fig.1, and deterioration is not annoying in the eyes of the user.

        After that, it is determined that process

20   continues or stops in step 505. If the process is continued, the process is repeated from the first step 501. If the process should be ends, the process ends.

        As mentioned above, the virtual viewpoint

25   image generation method using the virtual viewpoint image generation apparatus of this embodiment 1-1 does not intend to obtain the accurate geometrical model of the object for every case and for every portion like the conventional measure. In contrast,

30   the virtual viewpoint image generation method assumes that estimation values having enough reliability cannot be obtained in distance estimation according to photographing conditions and portions of the object. Thus, a portion in which an

35   estimation value having low reliability is obtained is rendered vaguely so that the portion contributes little to image generation to prevent extreme image

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deterioration. On the other hand, a portion in
which distance data having high reliability is
obtained is rendered clearly so that the portion
highly contributes image generation. Therefore,
5   deterioration of image of the portion having low
estimation reliability can be inconspicuous so that
the virtual viewpoint image having small
deterioration can be obtained in the eyes of the
user.
10   In addition, the virtual viewpoint image
generation apparatus 1 of this embodiment 1-1, since
the virtual viewpoint image can be generated using
texture mapping, workload of the apparatus in the
image generation processing can be decreased and the
15   virtual viewpoint image can be generated at high
speed.
          In addition, the virtual viewpoint image
generation apparatus 1 does not need to be a
specific apparatus. For example, the virtual
20   viewpoint image generation apparatus 1 can be
realized by a computer including a CPU and a storing
device such as a memory and a hard disk and the like,
and a program, for example. In such a case, by
generating a program that can cause the computer to
25   execute each step shown in Fig.11 and by executing
the program on the computer, the virtual viewpoint
image having small image deterioration can be easily
generated at high speed even though the computer is
a general personal computer. In this case, data for
30   the processing is held in the storing apparatus and
read as necessary so as to be processed by the CPU.
          The program can be provided by storing in
a recording medium such as a floppy disk or CD-ROM,
and can be provided via a network.
35   The configuration of the virtual viewpoint
image generation apparatus, the generation method
and the processing procedure of the virtual

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viewpoint image described in this embodiment 1-1 are
merely examples. The principal object of the
present invention is to determine transparency
information of the multi-layered projection planes

5　according to reliability of corresponding regions
among images obtained by taking the object from
plural different viewpoints. Thus, within a limit
that does not largely differ from the scope, the
present invention is not dependent on a particular

10　processing method or implementation.

In addition, systems using the virtual
viewpoint image generation apparatus 1 are not
limited to the system of one direction shown in
Fig.7. The present invention can be applied to a

15　bi-directional system.

Fig.18 is a schematic diagram showing an
application example of a system to which the virtual
viewpoint image generation apparatus 1 of this
embodiment 1-1 is applied.

20　The virtual viewpoint image generation
apparatus 1 of the embodiment 1-1 is applicable for
a system, such as TV phone, TV conference and the
like, for example. For example, as shown in Fig.18,
the virtual viewpoint image generation apparatus 1

25　can be applied to a system for supporting visual
communications in which a user A and a user B
remotely existing via a communication network
present an image with each other while both users
regard the other party as a user and an object. In

30　the system, assuming that an image of the user B
viewed from a viewpoint desired by the user A is
Img[A→B], Img[A→B] is generated based on an image of
the user B photographed by the object taking means
(camera) 3B in the user B side, so that the image is

35　provided to the image display means 4A in the side
of the user A. Assuming that an image of the user A
viewed from a viewpoint desired by the user B is

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Img[B→A], Img[B→A] is generated based on an image of
the user A photographed by the object taking means
(camera) 3A in the user A side, so that the image is
provided to the image display means 4B in the side
5   of the user B.

In the system shown in Fig.18, an example
is shown in which the viewpoint position input means
of each User is configured by a data transmission
means 201A, 201B and a data receiving means 202A,
10   202B in a position/posture sensor mounted on a head
of the user, and the viewpoint position input means
automatically follows movement of the head of the
user so as to calculate a desired virtual viewpoint.
However, the viewpoint position input means does not
15   necessarily adopt such configuration. The same
function can be realized by estimating the position
/ posture of the head based on the image of the user
photographed by the object taking means 3A, 3B.

In the system, Img[A→B] can be generated
20   in any of the virtual viewpoint image generation
apparatus 1A in the user A side and the virtual
viewpoint image generation apparatus 1B in the user
B side. In the former case, the image of the user B
taken by the camera 3B is transmitted to the virtual
25   viewpoint image generation apparatus 1A in the user
A side via the network 8, and the Img[A→B] is
generated by the virtual viewpoint image generation
apparatus 1A based on the image and is presented by
the image display means 4A. In the latter case, the
30   image of the user B taken by the camera 3B in the
user B side is generated by the virtual viewpoint
image generation apparatus 1B in the user B side.
After that, the virtual viewpoint image Img[A→B] is
transmitted to the virtual viewpoint image
35   generation apparatus 1A in the user A side and is
presented by the image display means 4A. In
addition, although not described in detail, similar

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procedure can be adopted for Img[B→A].

In addition, each means forming the image generation means 103 in Fig.6 can be provided in any one of the virtual viewpoint image generation

5   apparatus 1A in the user A side and the virtual viewpoint image generation apparatus in the user B side. For example, for generating the Img[A→B], the projection plane determination means 103a, the reference viewpoint determination means 103b and the

10   corresponding point matching means 103d are provided in the image generation apparatus 1A in the user A side, and the texture array keeping means 103c, the color information determination means 103e, the existence probability information determination

15   means 103f and the rendering means 103g can be provided in the image generation apparatus 1B in the user B side. Although detailed description is not provided, similar configuration can be adopted for Img[B→A].

20   In addition, in any place on the network 8, an image generation apparatus 1C can be provided separately from the virtual viewpoint image generation apparatuses 1A and 1B, so that all or a part of image generation means can be provided in

25   the image generation apparatus 1C.

Although communications between two users of user A and user B are described, the number of users are not limited to two. The present invention can be applied to more users. In the case, assuming

30   a virtual space used for communication separately from the actual space in which users actually exist, by providing an image of other user according to position relationship with each other, the system can provide users with feeling as if to share

35   virtual space (cyber space) on the network.
(Embodiment 1-2)
Figs.19A and 19B are schematic diagrams

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for explaining a virtual viewpoint image generation
method of the embodiment 1-2. Fig.19A is a flow
diagram indicating processing that is a feature of
this embodiment 1-2. Fig.19B is a flow diagram

5   showing an example of concrete processing procedure
of steps for determining transparency information.

In the embodiment 1-2, an example is
described in which image generation is performed by
converting the existence probability information

10   into transparency information instead of using the
existence probability information of the projection
point calculated in the step 5031 in generation
processing for virtual viewpoint image described in
the embodiment 1-1.

15   In this example, as to the configuration
of the virtual viewpoint image generation apparatus
1 and the general processing procedure, forms
similar to examples described in the embodiment 1-1
can be adopted. Thus, only parts having differences

20   with respect to the embodiment 1-1 are described in
the following.

In the embodiment 1-1, in step 503 for
generating the image, the virtual viewpoint image is
generated using the existence probability

25   information β_j determined in step 5031 as shown in
Fig.11. On the other hand, in this embodiment 1-2,
as shown in Fig.19A, a step 503p is added for
determining transparency by converting the existence
probability information after the step 5031.

30   Therefore, although the array for storing
color information and the existence probability
information is kept in the step 503d for keeping
texture array in the embodiment 1-1, the array is
kept for storing color information and the

35   transparency information in the step 503d in this
embodiment 1-2.

The transparency information α_j is

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calculated based on the existence probability information β_j. In the same way as the step 5011 of the embodiment 1-1, also in this embodiment 1-2, the existence probability information is calculated once in the step 5031 and the transparency information is calculated in the next step 503p.

In step 503c for performing rendering processing in this embodiment 1-2, D_j is successively calculated according to equations from the equation 2 to the equation 4 instead of using the equation 26 and the equation 27 described in the embodiment 1-1. Therefore, color information K_j^* of the pixel $p^*(u_p^*, v_p^*)$ on the image plane is calculated using the following equation 28.

[Equation 28]

$$
\begin{aligned}
K_P^* &= D_M \\
&= \alpha_M K_M + (1-\alpha_M)\alpha_{M-1}K_{M-1} + \cdots \\
&\quad + (1-\alpha_M)(1-\alpha_{M-1})\cdots(1-\alpha_2)\alpha_1 K_1
\end{aligned}
$$

The image generation method in this embodiment is described so far. An example of a method for calculating the transparency information α_j based on the existence probability information β_j is described as follows.

First, by comparing the equation 26 and the equation 28, the following equation 29 is obtained.

[Equation 29]

$$
\begin{cases}
\beta_M = \alpha_M \\
\beta_j = \left\{ \displaystyle\prod_{m=j+1}^{M}(1-\alpha_m) \right\} \alpha_j \quad (j \in J)
\end{cases}
$$

Based on this relationship, a procedure for obtaining α_j in an order of j=M,M-1,…,1 is as

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follows.

First, as shown in Fig.19B, M is assigned to j (j=M) as an initial value of j (step 5031p). Next, α_M is determined as $\alpha_M=\beta_M$ from the equation 29
5   (step 5032p). Next, the value of j is updated to j=j-1 (step 5033p).

Next, it is determined whether α_{j+1} is 1 (step 5034p). At this time, if $\alpha_{j+1}\neq1$, α_j is determined by the following equation 30 from the
10 relationship of the equation 29 (step 5035p).
    [Equation 30]

$$\alpha_j = \frac{1}{\displaystyle\prod_{m=j+1}^{M}(1-\alpha_m)}\beta_j$$

On the other hand, if $\alpha_{j+1}=1$, α_j is determined by the following equation 31 (step 5036p)
15 [Equation 31]

$$\alpha_j = 1$$

The reason is described as follows. First, when $\alpha_{j+1}=1$, the following equation holds true. Thus, the equation 30 cannot be calculated since the
20 denominator is 0.
    [Equation 32]

$$\prod_{m=j+1}^{M}(1-\alpha_m)=0$$

Thus, the following equation 33 is obtained by expanding the equation 32. Then, the equation 34 is
25 obtained by substituting the equation 29.
    [Equation 33]

$$\alpha_M + (1-\alpha_M)\alpha_{M-1} + \cdots$$
$$+ (1-\alpha_M)(1-\alpha_{M-1})\cdots(1-\alpha_{j+2})\alpha_{j+1} = 1$$

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[Equation 34]

$$\beta_M + \beta_{M-1} + \cdots + \beta_{j+1} = 1$$

The following equation 35 is obtained from the equation 34, the equation 22 and the equation 23.

5　[Equation 35]

$$\beta_j = 0$$

By substituting the equation 32 and the equation 35 into the lower side of the equation 29, $0 = 0 \times \alpha_j$ is obtained, so that it can be understood that α_j can

10　take any value. Therefore, in this embodiment 1-2, α_j is set as 1 ($\alpha_j = 1$), for example.

However, as mentioned above, α_j can be set as any value, and the present invention is not dependent on a particular determining method of α_j.

15　Next, it is determined whether processing completes up to j=1 (step 5037p). When every processing completes, the procedure ends, when every processing does not end yet, the procedure returns to the step 5033p.

20　As described above, according to the virtual viewpoint image generation method of the embodiment 1-2, like the embodiment 1-1, the virtual viewpoint image in which partial image deterioration is inconspicuous can be generate easily and at high

25　speed.

As described in the embodiment 1-1, in image generation using the existence probability information as it is, there may be a case in which brightness increases near the blocking area of the

30　object when the reference viewpoint and the virtual viewpoint are different. On the other hand, as described in the embodiment 1-2, in the image generation for converting the existence probability information to transparency, there is an effect to

35　prevent the phenomenon. Therefore, a virtual

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viewpoint image having small image deterioration and more similar to the actual object can be obtained.

In addition, as described in the embodiment 1-1, in the image generation using the
5　existence probability information as it is, there is no guarantee that color information calculated by an equation described later falls within an effective limit when the reference viewpoint and the virtual viewpoint are different, so that correction
10　processing is required, for example. On the other hand, according to the image generation for converting the existence probability information to transparency like the embodiment 1-2, such correction is not necessary. Therefore, the image
15　generation processing can be simplified.

In addition, in image generation for converting the existence probability information to the transparency like the virtual viewpoint image generation method of this embodiment 1-2, a
20　semitransparent object can be efficiently represented, so that there is an effect that the present invention can be applied to more objects in the actual world.

The virtual viewpoint image generation
25　method described in this embodiment 1-2 is an example, and the principal object of the present embodiment is to generate the virtual viewpoint image by converting the existence probability information to the transparency. Therefore, the
30　present invention is not dependent on particular calculation method or processing procedure within a limit largely exceeding the object.

The color information corresponds to brightness information for black and white images,
35　and the same procedure can be applied.

(Embodiment 1-3)

Fig.20 is a schematic diagram for

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explaining the virtual viewpoint image generation
method of the embodiment 1-3.　The figure shows
examples of projection plane group, reference
viewpoint, virtual viewpoint and projection points.

5　　　　　　　In the embodiment 1-3, a method for image
generation is described in which the projection
plane L_j common for plural cameras is not used but
projection planes specific for each camera C_j are
set.　Since the configuration of the virtual

10　viewpoint image generation apparatus 1 and general
processing procedure for image generation in this
embodiment are the same as those described in the
embodiment 1-1, detailed descriptions are not
provided.

15　　　　　　　First, as described in the embodiment 1-1,
the virtual viewpoint is determined in the step 501,
and the images of the object is obtained in the next
step 502.

　　　　　　　In the image generation method of this

20　embodiment 1-3, projection plane groups specific for
each camera are set in the next step 503 in
generation of the virtual viewpoint image.

　　　　　　　At this time, as shown in Fig.20, for
example, the projection plane groups are set as

25　projection plane groups $\Lambda_i \equiv \{L_{ij} | j \in J\}$ each parallel
to the image surface $Img_i (i \in I)$ specific to each
camera $C_i (i \in I, I = \{n-1, n, n+1, n+2\})$.

　　　　　　　After setting the projection plane groups,
next, in processing for determining the reference

30　viewpoint in the step 503b, each reference viewpoint
R_i specific to the projection plane group Λ_i is set
in a position the same as the viewpoint C_i of the
camera.

　　　　　　　Next, after completing the step 503b,

35　processing of the 503c is performed according to the
procedure described in the embodiment 1-1.　Then, in
the next step 503d, each pixel of the digital image

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taken by the camera is reverse-projected on the
projection planes so that the pixel of the digital
image is associated with each pixel of the texture
array of the projection planes.

5   Conversion from the point (u,v) of the
digital image to the point (x,y) on the image plane
is represented by the equation 17, for example.
Reverse-projection from (x,y) to the point (X,Y,Z)
on the projection plane in the three-dimensional

10   space can be mathematically expressed as follows,
for example.

             Generally, when a two-dimensional point
(x,y) is given, there are an infinite number of
three-dimensional points that satisfy the equation

15   14 and the equation 15. In the points, points
(X,Y,Z) existing on the projection plane are the
reverse-projection image.

             An equation of the projection plane is
generally expressed as aX+bY+cZ+d=0. A following

20   equation 36 is obtained by rewriting this equation
by vector representation.

   [Equation 36]

$$\begin{bmatrix} a & b & c & d \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = 0$$

             By integrating the equation 14, the equation 15 and

25   the equation 36, the following equation 37 can be
obtained.

   [Equation 37]

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$$s\begin{bmatrix} x \\ y \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} \\ a & b & c & d \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

The reverse-projection image from (x,y) to (X,Y,Z)
can be obtained by solving the equation 37 with
respect to (X,Y,Z). When the matrix of 4 rows and 4
5 columns in the equation 37 has an inverse matrix, by
substituting S' for 1/s, the reverse-projection
image can be obtained by the following equation 38.

[Equation 38]

$$s'\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} \\ a & b & c & d \end{bmatrix}^{-1}\begin{bmatrix} x \\ y \\ 1 \\ 0 \end{bmatrix}$$

10 The above-mentioned example is an example to the
utmost. Calibration for correcting aberration of a
lens (distortion, for example) can be performed, and
the point (X,Y,Z) on the projection plane
corresponding to the point (u,v) of the digital
15 image can be held as a table.
       After that, processing from the step 503e
to the step 503g is performed according to the
procedure described in the embodiment 1-1. Then, in
the processing for determining the color information
20 in the next step 503h, color information of the
projection points on the projection plane group Λ_i
are determined only by using the color information
of the image taken by the camera C_i.
       By performing the procedures of the step
25 503d and the step 503h described in this embodiment

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1-3, the digital image taken by the camera can be used as the color information of the texture array of the projection plane as it is.

     After that, again, the procedure from the step 503i to the step 503h is performed in the same way as the embodiment 1-1. Then, next, in the rendering means in the step 503o, mixing processing for color information is performed with respect to projection points overlapping when viewed from the virtual viewpoint P. At this time, for example, in the example shown in Fig.20, mixing processing for color information is performed on a line passing through the virtual viewpoint P for projection points on the projection plane groups Λ_n and Λ_{n+1}.

     Assuming that a projection point in the projection plane L_{ij} is T_{ij}, color information at T_{ij} is K_{ij}, and that existence probability information is β_{ij}, color information of the image plane of the virtual viewpoint P represented as the equation 27 in the embodiment 1-1 is determined in the following way, for example.

     That is, the color information K_p^* of a pixel $p^*(u_p^*, v_p^*)$ on the image plane is determined as an weighted average value of color information calculated by using weight coefficients of existence probability information $\{\beta_{ij}^* | i \in I, j \in J\}$ corresponding to color information $\{K_{ij}^* | i \in I, j \in J\}$ of projection point series $\{T_{ij}^* | i \in I, j \in J\}$ on a line connecting between P and p^* as shown in the following equation 39.

[Equation 39]

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$$K_P^* = \frac{\displaystyle\sum_{i \in I}\sum_{j=1}^{M}\beta_{ij}K_j^*}{\displaystyle\sum_{j=1}^{M}\beta_{ij}}$$

      As described above, according to the
virtual viewpoint image generation method of this
embodiment 1-3, the virtual viewpoint image in which
5   partial image deterioration is inconspicuous can be
generated easily and at high speed like the
embodiment 1-1.

      In addition, by setting the projection
plane groups specific to each camera irrespective of
10   position relationship among cameras like this
embodiment 1-3, even if the placement of the cameras
are complicated and irregular, processing of setting
the projection plane groups is not affected so that
image generation can be performed by the consistent
15   processing method.

      The virtual viewpoint image generation
method described in this embodiment 1-3 is an
example, and the principal object of the present
embodiment is to generate the virtual viewpoint
20   image by converting the existence probability
information to the transparency. Therefore, the
present invention is not dependent on particular
calculation method or processing procedure within a
limit largely exceeds the object.
25   The color information corresponds to
brightness information in the case using black and
white images, and same procedure can be applied.
      (Effects of first embodiment)
      The method described in the first
30   embodiment does not intend to obtain a geometrical
object model accurate for every case and every

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portions like the conventional method. But, under
the assumption that an estimated value having
adequate reliability cannot be obtained in the
distance estimation depending on picture-taking
5   conditions and portions, a portion by which an
estimated value of low reliability is obtained is
drawn vaguely so as to provide the portion with low
contribution to image generation for avoiding
extreme image deterioration, and a portion, by which
10   distance data of high reliability is obtained, is
drawn clearly so as to provide the portion with high
contribution to image generation. Therefore, image
deterioration of the poison of low estimation
reliability can be inconspicuous.
15   In addition, the problem that the
brightness increases near the blocking area when the
reference viewpoint and the virtual viewpoint are
different can be solved. When the reference
viewpoint and the virtual viewpoint are different,
20   there is no guarantee that calculated color
information falls within an effective limit of color
information. Thus, correction processing may be
necessary. On the other hand, according to the
method described in this embodiment, such correction
25   is unnecessary. In addition, a semitransparent
object can be efficiently represented, so that there
is an effect that the present invention can be
applied more widely to more objects in the actual
world. In addition, since the groups of the
30   projection planes specific to each camera are set
irrespective of position relationship among cameras,
even if placement of the cameras is complicated or
at random, processing for setting the groups of the
projection planes is not affected so that image
35   generation can be performed by consistent processing
method.
        Further, when setting the projection plane

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groups specific to each camera, it is not necessary
to perform mixing processing among images taken by
corresponding cameras as to color information of the
projection planes. Therefore, parallel processing

5   can be performed when performing processing by a
computer, so that speed of the image generation can
be increased.

In addition, since color information of a
projection plane group associated with the same

10   camera are the same, the texture memory for storing
the color information can be shared. Therefore, the
memory is not so consumed even when the number of
projection planes increases, so that workload of the
apparatus used for image generation can be decreased.

15   In addition, since a camera corresponding to a
projection plane is uniquely determined, calibration
such as correction of distortion of a lens can be
performed easily and quickly by setting
correspondence of coordinates of them beforehand.

20   In addition, processing time for
performing the processing by the apparatus for
generating the virtual viewpoint image based on the
images of the object can be decreased, or the
workload of the apparatus can be decreased, so that

25   even a general personal computer can generate an
image having small partial deterioration in a short
time.

[Second embodiment]

In the following, the second embodiment of

30   the present invention is described. The second
embodiment mainly corresponds to the claims 12-21.
Although the basic mechanism of the second
embodiment is the same as that of the first
embodiment, the second embodiment is characterized

35   in that plural groups of camera sets are provided
and the existence probability is calculated based on
correlation degree obtained for each camera set. In

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figures for explaining the second embodiment, the
same reference signs are assigned for the same
functions.

5   The image generation method of the second
embodiment is a method for obtaining, from plural
images of different viewpoints, a three-dimensional
shape of an object appearing in the images, and
generating an image for providing the three-
dimensional image of the object or generating an
10   image of the object viewed from arbitrary viewpoints.
The three-dimensional shape of the object is
obtained by estimating distance from the observer's
viewpoint to each point of the surface of the object
by setting multi-layered projection planes using the
15   texture mapping method. When estimating the
distance to the surface of the object, correlation
degree between the projection point and each
corresponding point of the image (to be referred as
corresponding point hereinafter) is obtained for
20   each of points (to be referred to as projection
point hereinafter), on the projection planes,
overlapping when viewed from the observer's
viewpoint. Then, an projection point near which the
surface of the object exists is estimated among the
25   overlapping projection points according to the
correlation degree of the projection points
overlapping when viewed from the observer's
viewpoint. In the image generation method of this
embodiment, it is not considered that the surface of
30   the object exists at a neighborhood of projection
point among plural projection points overlapping
when viewed from the observer's viewpoint. But, it
is considered that the surface of the object exists
in a neighborhood of each projection point in a
35   ratio according to the correlation degree of each
projection point. In the image generation method of
this invention, a probability (to be referred to as

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existence probability) that the surface of the
object exists at the projection point or the
neighborhood is determined according to the
correlation degree of each projection point. Then,
5   when the image is generated based on the three-
dimensional shape of the object, the color
information of the projection point is assigned to
the color information of each point of the image to
be generated according to the value of the existence
10   probability. Accordingly, from the viewpoint of the.
observer who observes the projection planes, a
portion at which estimation of the distance to the
object surface is difficult is rendered vaguely, so
that discontinuous noise and the like becomes
15   inconspicuous.
        In addition, with respect to the plural
projection points overlapping when viewed from the
observer's viewpoint or from the reference viewpoint
for obtaining the three-dimensional shape of the
20   object, if probability density distribution of the
existence probability of the object surface can be
estimated to some extent, the existence probability
can be obtained using a parameter function p(l) to
which the probability density distribution is
25   reflected. In such a case, variation of the
correlation degree due to noise of the taken images
can be decreased so that deterioration of
reliability of the existence probability can be
prevented.
30   In addition, instead of obtaining the
correlation degree for a projection point using
corresponding points of all images, by obtaining it
using corresponding points of images taken from some
predetermined viewpoints, reliability of the
35   correlation degree improves so that reliability of
the existence probability improves by removing each
image in which the object does not appear due to

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occlusion even though the surface of the object exists on the projection point.

　　　Figs.21-28 are schematic diagrams for explaining the principle of the image display method

5　in this embodiment. Fig.21 is a diagram for explaining a concept of a method for generating the image to be displayed. Fig.22 is a diagram representing Fig.21 in two-dimensional. Fig.23A and Fig.23B are diagrams for explaining a method for

10　obtaining the correlation degree of the corresponding point. Fig.24A and Fig.24B are diagrams for explaining a problem when obtaining the correlation degree of the corresponding point. Fig.25 is a diagram for explaining a method for

15　solving the problem when obtaining the correlation degree. Fig.26A and Fig.26B are diagrams for explaining an example of a method for improving accuracy of the existence probability. Fig.27A, Fig.27B and Fig.28 are diagrams for explaining

20　characteristics of this embodiment.

　　　In the image display method of this embodiment, when generating the image to be displayed, first, a virtual three-dimensional space is set in the image generation apparatus such as a

25　computer. Then, on the three-dimensional space, viewpoints $C_i (i=1,2,…,N)$ of cameras that take the images of the object and projection planes $L_j (j=1,2,…,M)$ having a multi-layered structure for estimating the three-dimensional shape of the object

30　are set. At this time, when the cameras are arranged on a line, the viewpoints C_i are set on the X axis (z=0) as shown in Figs.21 and 22, for example. As the projection planes L_j, planes parallel to the XY plane $Z=l_j (<0)$ are set as shown in Figs.21 and 22,

35　for example.

　　　As shown in Figs.21 and 22, if there is the surface of the object at an intersection point

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T_m between a line lp extending from the observer's viewpoint p and a projection plane L_m, the point should be taken on a point (corresponding point) $G_{i,m}$ on the image photographed by the camera placed at
5   the viewpoint C_i. In the same way, when the surface of the object exists at the projection point T_m, the point should appear at each of corresponding points $G_{i+1,m}$ and $G_{i+2,m}$ on images taken by the cameras placed at the viewpoints C_{i+1} and C_{i+2} respectively.
10   Therefore, if the correlation degrees (similarity) of the corresponding points $G_{i,m}$, $G_{i+1,m}$ and $G_{i+2,m}$ on each image for the projection point T_m are obtained, it can be estimated whether the surface of the object exists at the projection point T_m or the
15   neighborhood. By performing the estimation for each projection point T_j on the line lp extending from the observer's viewpoint P, a neighborhood of a projection point T_j (projection plane L_j) at which the surface of the object exists can be estimated on
20   the line lp extending from the observer's viewpoint p.
     When estimating a neighborhood of a projection point T_j (projection plane L_j), on the line lp extending from the observer's viewpoint p,
25   where the surface of the object exists, correlation degree Q_j of each corresponding point $G_{i,j}$ corresponding to the projection point T_j is used. The correlation degree Q_j is obtained using the following equation 40 in the same way as the first
30   embodiment.
     [Equation 40]

$$Q_j = \sum_{i \in I} \left(K_j - K_{ij} \right)^2$$

wherein I is a set of viewpoints C_i that can define corresponding points $G_{i,j}$ for the projection point T_j
35   on the image planes in the viewpoints $C_i (i=1, 2, …, N)$,

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K_{ij} is color information of each corresponding point $G_{i,j}$, and K_j is color information of the projection point T_j and is an average value of color information K_{ij} of each corresponding point $G_{i,j}$.

5 　　　　At this time, a case is considered in which the result shown in Fig.23A is obtained, for example, when superimposing the actual surface shape of the object on the established projection plane L_j. At this time, in projection points T_j on the line lp extending from the observer's viewpoint p, the

10 projection point T_m is the nearest to the object surface that can be viewed from the viewpoints C_i, C_{i+1} and C_{i+2} of the cameras. Thus, as shown in Fig.23A, points of the object surface appearing in

15 the corresponding points $G_{i,m}$, $G_{i+1,m}$ and $G_{i+2,m}$ corresponding to the projection point T_m are very close with each other. On the other hand, for example, the points of the object surface appearing in corresponding points corresponding to the

20 projection point T_2 are apart with each other. As a result, when obtaining the correlation degree Q_j of each projection point T_j on the line lp, only the correlation degree Q_m for the projection point T_m is very small value as shown in Fig.23B. Therefore,

25 when being viewed from the observer's viewpoint P in the direction of the line lp, the surface of the object can be estimated to exist at a position of the projection point T_m, that is, at a a distance l_m at which the projection plane L_m is set.

30 　　　　Thus, by providing lines lp from the observer's viewpoint P in various directions and repeating similar processing for projection points T_j on each line lp, the surface shape of the object appearing in the images can be estimated.

35 　　　　However, such estimation method is effective, that is, the reliability of the estimated surface shape of the object is high, only in the

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case where the actual surface shape of the object is
relatively simple as shown in Fig.23A and 23B. When
the shape of the object is complicated or when
plural objects overlap when being viewed from the
5   observer's viewpoint, the reliability of the
estimated surface shape of the object is lowered.

   As an example in which the reliability of
the estimated surface shape is lowered, a case is
considered in which the result shown in Fig.24A is
10   obtained, for example, when two objects overlaps
with respect to the observer's viewpoint and when
superimposing the projection planes L_j with the
surface shapes of the two objects. In this case, it
can be considered that the correlation degree Q_j for
15   the projection points T_j on the line lp extending
from the observer's viewpoint P as indicated by a
dotted line in Fig.24A provides distribution shown
in Fig.23B, for example. Thus. it can be considered
that the reliability of the estimated surface shape
20   of the object A is high near the line lp.

   However, when obtaining the correlation
degree Q'_m for the projection point T'_m on the line
lp' extending from the observer's viewpoint P as
shown by the solid line shown in Fig.24A, the
25   surface of the object B appears at the corresponding
point $G'_{i,m}$ of the image taken from the viewpoint C_i
and the surface of the object A appears at the
corresponding points $G'_{i+1,m}$ and $G'_{i+2,m}$ of the images
taken from the viewpoints $C_{i+1,m}$ and $C_{i+2,m}$. In such a
30   case, the correlation degree Q'_m obtained by the
equation 40 becomes large. As a result,
distribution of the correlation degree Q'_j of the
projection points T'_j on the line lp' becomes one
shown in Fig.24B, so that it is difficult to
35   estimate a neighborhood of a projection point T_j at
which the surface of the object exists. At this
time, when it is estimated that the surface of the

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object exists near a projection point T'$_j$ having the smallest correlation degree Q'$_j$ like the case having the distribution shown in Fig.23B, discontinuous noise appear on the image to be displayed if the
5   estimation is not correct.

        Thus, according to the image display method in this embodiment, such estimation is not performed in which the surface of the object is estimated to exist at the projection point T$_j$ or the
10   neighborhood at which the correlation degree Q$_j$ is the smallest, but it is considered that the surface of the object exists at each projection point T$_j$ in a probability according to the ratio of the size of the correlation degree Q$_j$. At this time, assuming
15   that the probability (existence probability) that the surface of the object exists at the projection point T$_j$ or the neighborhood is β$_j$, the existence probability β$_j$ of projection points on the line lp extending from the observer's viewpoint P, that is,
20   projection points T$_j$ overlapping when viewed from the observer's viewpoint P, requires to satisfy conditions as shown in the following equations 41 and 42.

    [Equation 41]

25   $$0 \le \beta_j \le 1$$

    [Equation 42]

$$\sum_{j=1}^{M} \beta_j = 1$$

    For the existence probability β$_j$ to take a value nearer to 1 as the probability of existence of the
30   object surface is higher in projection points T$_j$, the existence probability β$_j$ of each projection point T$_j$ is determined by performing conversion processing represented by the following equations 43

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and 44 for the correlation degree Q_j of each
projection point T_j.
     [Equation 43]

$$\tilde{\beta}_j = \frac{1}{Q_j}$$

5   [Equation 44]

$$\beta_j = \frac{\beta_j}{\sum\limits_{j=1}^{M} \tilde{\beta}_j}$$

The existence probability β_j only needs to satisfy
the conditions of the equations 41 and 42. Thus,
the existence probability β_j can be determined in a
10   method other than the conversion processing
represented by the equations 43 and 44.
          According to such processing, by
determining the probability β_j that the surface of
the object exists at the projection point T_j or the
15   neighborhood, the color information K_j and the
existence probability β_j for each projection point T_j
on the line lp extending from the observer's
viewpoint P can be determined.
          When displaying a three-dimensional image
20   of an object on a DFD of brightness modulation type
by using the three-dimensional shape of the object
estimated in this way, for example, each pixel
corresponding to each projection point T_j in plural
display planes is displayed with brightness
25   according to the color information K_j and the
existence probability K_j. Accordingly, as to
correlation degrees Q_j of each projection point T_j on
the line lp, when only a correlation degree Q_m of a
projection point T_m is far different from other
30   correlation degrees as shown in Fig.23B, only the

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existence probability β_m of the projection point T_m takes a large value. Therefore, brightness of only a pixel corresponding to the projection point T_m becomes large so that the pixel looks clear for the

5 observer who observes the projection plane L_j from the observer's viewpoint.

On the other hand, when correlation degrees Q_j of each projection point T_j on the line lp are as shown in Fig.24B so that it is difficult to

10 estimate a projection point T_j near which the surface of the object exists, plural projection points having similar existence probability appear. Therefore, plural pixels corresponding to the projection points T_j on the projection planes L_j are

15 displayed with similar brightness, so that sense of distance of the pixels becomes vague when viewed from the observer who observes the projection planes L_j from the observer's viewpoint. However, since the surface image of the object is displayed on

20 plural projection points overlapping when viewed from the observer's viewpoint P, discontinuous noise that may appear due to an error of estimation for the distance of the object surface does not appears. Therefore, even though the accurate three-

25 dimensional shape of the object to be displayed is not obtained, a three-dimensional image of the object that looks natural for the observer can be displayed.

In addition, when displaying the two-

30 dimensional image (arbitrary viewpoint image) of the object viewed from an arbitrary viewpoint using the three-dimensional shape of the object estimated by the procedure, color information of a cross point between the line lp and the image plane of the image

35 to be displayed is determined as color information obtained by mixing color information K_j of each projection point T_j on the line lp extending from

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the observer's viewpoint in a ratio of the existence probability β_j.

If the probability density distribution of the probability that the surface of the object

5 exists can be estimated to some extent when determining the existence probability β_j, error of estimation due to noise of the images taken at the viewpoints C_i can be decreased by performing statistical processing, based on the shape

10 distribution of the object, on the existence probability β_j of each projection point T_j determined by the equations 43 and 44. To differentiate between the existence probability before performing the statistical processing and the existence

15 probability after performing the statistical processing, it is assumed that the existence probability before performing the statistical processing, that is, the existence probability β_j obtained by the equation 43 and the equation 44 is

20 regarded as an evaluation reference value v_j. Then, it is assumed that a value obtained by performing the statistical processing on the evaluation reference value v_j is the existence probability β_j.

In the statistical processing performed on

25 the evaluation reference value v_j obtained by the equation 43 and the equation 44, first, as shown in Fig.26A, for example, a distribution function $p(l)$ of the existence probability is obtained by applying the probability density distribution of the

30 existence probability of the object to the distribution of the evaluation reference value v_j. At this time, when the probability density distribution complies with normal distribution (Gaussian distribution), for example, the

35 distribution function $p(l)$ of the existence probability can be represented by the following equation 45.

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[Equation 45]

$$p(l) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(l-\mu)^2}{2\sigma^2}\right\}$$

In the equation, μ indicates an average value, and σ
indicates a parameter indicating dispersion. Using
5   the estimation reference value ν_j, estimation can be
performed as shown in the following equation 46 and
the equation 47.
[Equation 46]

$$\mu = \sum_{j=1}^{M} \beta_j l_j$$

10   [Equation 47]

$$\sigma^2 = \sum_{j=1}^{M} \left(\beta_j l_j - \mu\right)^2$$

After the distribution function p(l) of the
existence probability is obtained in such a way, the
existence probability β_j is determined using the
15   equation 48, for example.
[Equation 48]

$$\beta_j = \int_{l_j^-}^{l_j^+} p(l) dl$$

In the equation, l_j^- and l_j^+ respectively are an
lower limit value and an upper limit value of a
20   distance at which the object surface is regarded to
exist on a projection plane L_j at a distance of l_j.
The values l_j^- and l_j^+ can be provided by the
following equation 49 and the equation 50, for
example.
25   [Equation 49]

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$$l_j^- = \frac{l_{j-1} + l_j}{2}, \quad l_j^- = -\infty$$

[Equation 50]

$$l_j^+ = \frac{l_j + l_{j+1}}{2}, \quad l_M^+ = \infty$$

Based on the existence probability ν_j obtained by

5   using the relationships of the equations 45-50, by
displaying the three-dimensional image of the object
on the DFD or by displaying the two-dimensional
image viewed from an arbitrary viewpoint, an image
in which noise effect of the original images is

10   reduces can be displayed, wherein the original
images are the images obtained by taking the object
from the viewpoints C_i.

In addition, as shown in Figs.24A and 24B,
for example, when an object different from one

15   appearing at other corresponding points appears in a
corresponding point $G_{i,j}$ corresponding to a
projection point T_j due to occlusion of the object,
it can be considered that relatively reliable
estimation can be performed by obtaining the

20   correlation degree Q_j by excluding the corresponding
point. Considering the case shown in Fig.24A,
according to the method described so far, when
obtaining the correlation degree Q'_m of the
projection point T'_m on the line lp' extending from

25   the observer's viewpoint P, the corresponding point
$G_{i,m}$ at which the surface of the object B, not object
A, appears is also used. Therefore, the correlation
degree Q'_m obtained from the equation 40 becomes
large so that it is difficult to estimate a distance

30   at which the surface of the object exists on the
line lp'.

Thus, for example, as shown in Fig.27A,
the correlation degree Q_m for the projection point T_m

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is obtained by excluding the corresponding point $G_{i,m}$ at which the surface of the object B appears. At this time, in the example shown in Fig.27A, the correlation degree Q_m is obtained using

5 corresponding points $G_{i+1,m}$ and $G_{i+2,m}$ corresponding to the projection point T_m. By doing so, since points very close to the surface of the object A appear on the corresponding points $G_{i+1,m}$ and $G_{i+2,m}$, distribution shown in Fig.27B is obtained when

10 obtaining the correlation degree Q'_j from the equation 40, in which only the correlation degree Q'_m of the projection point T'_m is smaller than correlation degrees of other projection points. Therefore, effects of the occlusion can be decreased

15 so that a three-dimensional shape close to an actual surface shape of the object can be estimated.

In addition, at this time, several groups of sets of Ξ that is a set of corresponding points $G_{i,j}$ (viewpoints C_i) are set for obtaining the

20 correlation degree Q_j, and the correlation degree Q_j of each projection point T_j on the line lp extending from the observer's viewpoint P is obtained for every set of Ξ. Then, the results are integrated so as to obtain a final existence probability.

25 Generally, assuming that a group of corresponding points $G_{i,j}$ (viewpoints C_i) is $\Xi_h(h\in H)$, distribution function of the existence probability on the line lp obtained by using each group Ξ_h is $p_h(l)$, and that the existence probability obtained by each

30 distribution function $p_h(l)$ is $\beta_{j,h}$, the integrated existence probability β_j can be obtained by the following equation 51.

[Equation 51]

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$$\beta_j = \frac{\sum_{h \in H} \beta_{j,h}}{\sum_{h \in H}}$$

The color information K_j of the projection point T_j can be obtained using the following equation 52, for example, from color information $K_{j,h}$ and existence
5　probability $\beta_{j,h}$ obtained for each group Ξ_h.

[Equation 52]

$$K_j = \frac{\sum_{h \in H} \beta_{j,h} K_{j,h}}{\sum_{h \in H} \beta_{j,h}}$$

Accordingly, as shown in Fig.28, for example, a distribution function $p_h(l)$, obtained by a group Ξ_h,
10　by which reliability for estimating the distance to the object surface is high and a clear peak appears is not susceptible to another distribution function $p_h(l)$, obtained by another group Ξ_h, by which reliability for estimating the distance to the
15　object surface is low. Therefore, reliability for estimating the distance to each point of the object from the observer's viewpoint improves as a whole.

(Embodiment 2-1)

Figs.29-34 are schematic diagrams for
20　explaining an image generation method of the embodiment 2-1 of the present invention. Fig.29 is a flow diagram showing an example of a general processing procedure. Fig.30 is a flow diagram showing an example of a processing procedure of
25　steps for determining color information and existence probability of projection points in Fig.29. Fig.31 is a flow diagram showing an example of steps for determining the existence probability in Fig.30.

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Fig.32 is a diagram showing an example foe setting a camera set. Figs.33, 34A and 34B are diagrams for explaining a method for converting information of the projection plane to information of display plane.

5   The image generation method of this embodiment 2-1 is a method in which images taken from plural viewpoints are used, a three-dimensional shape of the object appearing on the images is obtained, and each two-dimensional image to be

10   displayed on each image display plane of the image display means having plural image display planes such as the DFD is generated, for example, based on the obtained three-dimensional shape of the object.

          The image generation method includes, as

15   shown in Fig.29 for example, a step 1 for obtaining the images of the object taken from the viewpoints C_i, a step 2 for setting the observer's viewpoint P, a step 3 for obtaining the three-dimensional shape of the object, a step 4 for converting color

20   information and existence probability of each point (projection point) on the projection planes representing the obtained three-dimensional shape to color information and existence probability of each point (display point) on the image display planes so

25   as to generate the two-dimensional images displayed on the image display planes, and a step 5 for displaying the display points on the image display planes with brightness or transparency according to the color information and the existence probability.

30   The step 3 includes, as shown in Fig.29 for example, a step 301 for setting projection planes L_j of a multi-layered structure, a step 302 for determining a reference viewpoint for obtaining the three-dimensional shape of the object, a step

35   303 for setting projection point series each including a group of projection points T_j, on the projection planes L_j, overlapping when viewed from

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the reference viewpoint and for setting
corresponding points $G_{i,j}$, on each obtained image,
corresponding to each projection point T_j of the
projection point series, a step 304 for determining
5   a group (to be referred as camera set) Ξ_h of
viewpoints C_i for obtaining correlation degrees Q_j of
each projection point T_j, a step 305 for keeping an
array for storing color information and existence
probability of the projection points T_j, and a step
10   306 for determining the color information and the
existence probability of the projection points T_j.

     In addition, as shown in Fig.30 for
example, the step 306 includes a step 30601 for
initializing the projection point series, a step
15   30602 for initializing the camera set Ξ_h and voting
data, a step 30603 for initializing the projection
point T_j on the projection point series, a step
30604 for determining the color information of the
projection point T_j, a step 30605 for calculating a
20   correlation degree $Q_{j,h}$ using corresponding points
included in the camera set Ξ_h among corresponding
points $G_{i,j}$ for the projection point T_j, a step 30606
for repeating the step 30604 and the step 30605 for
every projection point T_j on the projection point
25   series to be processed, a step 30607 for voting each
correlation degree $Q_{j,h}$ obtained for the camera set
Ξ_h, a step 30608 for updating the camera set Ξ_h, and
repeating processing from the step 30604 to the step
30607 for every camera set, a step 30609 for
30   determining existence probability of each projection
point T_j based on the correlation degree $Q_{j,h}$ voted in
the step 30607, and a step 30610 for updating the
projection point series and for repeating processing
from the step 30602 to the step 30609 for every
35   projection point series.

     In addition, as shown in Fig.31, the step
30609 includes a step 30609a for initializing the

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camera set Ξ_h, a step 30609b for calculating the evaluation reference value $\nu_{j,h}$ from the correlation degree $Q_{j,h}$ obtained by using the camera set Ξ_h, a step 30609c for determining the distribution

5 function $p_h(l)$ of the existence probability by performing statistical processing of the evaluation reference value $\nu_{j,h}$, a step 30609d for determining the existence probability $\beta_{j,h}$ of each projection point T_j from the distribution function of the

10 existence probability, a step 30609e for updating the camera set Ξ_h and repeating processing from the step 30609b to the step 30609d, and a step 30609f for determining the existence probability β_j of each projection point T_j by integrating the existence

15 probability $\beta_{j,h}$ obtained for each camera set Ξ_h.

When generating the two-dimensional images to be displayed on each image display plane of the DFD, for example, using the image generation method of this embodiment 2-1, images are obtained by taken

20 the object by cameras placed at plural different viewpoints C_i($i=1,2,…,N$) (step 1), first. At this time, the viewpoint C_i is a placement position of a camera for taking the image. For example, as shown in Fig.21, it is assumed that the cameras are

25 arranged one-dimensionally on a line. The arrangement of the viewpoints C_i of the cameras is not limited on the line, but the viewpoints may be arranged on plural lines or on a curve one-dimensionally. In addition, the viewpoints may be

30 arranged like two-dimensional lattice on a plane or a curved surface instead of one-dimensionally. Although color images or black and white images can be obtained as the obtained images, color images in which each point (pixel) on the image is represented

35 by color information using three primary colors of red (R), green (G) and blue (B) are obtained in this embodiment.

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      Next, the observer's viewpoint P from which the three-dimensional image of the object to be displayed on the DFD is observed is set on a virtual space in an image generation apparatus such

5   as a computer and the like (step 2).

      Next, the three-dimensional shape used for generating the image is obtained (step 3). In the step 3, first, projection planes L_j are set in the virtual space for estimating the three-dimensional

10   shape (surface shape) of the object (step 301). At this time, the projection planes L_j are set as planes parallel to the XY plane as shown in Fig.21, for example. The setting intervals of the projection planes L_j may be or may not be set to be

15   the same as the intervals of the image display planes of the DFD on which the images are displayed.

      Next, the reference viewpoint for obtaining the three-dimensional shape of the object is determined (step 302). The reference viewpoint

20   may be the observer's viewpoint, or may be any point on the three-dimensional space other than the observer's viewpoint.

      Next, projection point series each being a group of the projection points T_j, on each

25   projection plane L_j, overlapping when viewed from the observer's viewpoint P or the reference viewpoint, and corresponding points $G_{i,j}$, on the obtained images, corresponding to each projection point T_j are set (step 303).

30   The projection point T_j is represented as a point (X_j, Y_j, Z_j) on the virtual space (three-dimensional space), and the coordinates of the corresponding point $G_{i,j}$ are represented as $(x_{i,j}, y_{i,j})$ considering a two-dimensional xy coordinate system

35   on the image plane of the image taken from the viewpoint C_i. The coordinates $(x_{i,j}, y_{i,j})$ of·the corresponding point $G_{i,j}$ are obtained by projecting

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the projection point (X_j, Y_j, Z_j) to the image plane of the image taken from the viewpoint C_i. The general 3 rows and 4 columns conversion matrix described in the first embodiment can be used for the projection.

5   When using the image generation apparatus like a computer, the image to be processed is a so-called digital image, and is represented by a two-dimensional array in the memory of the apparatus. In the following, the coordinate system representing the position in the array is referred to as digital

10   image coordinate system, and the position is represented as (u, v). For example, considering a digital image of lateral 640 pixels and vertical 480 pixels, a position of each pixel of the digital

15   image can be represented by an argument u that may take any integer from 0 to 639 and an argument v that may take any integer from 0 to 479. The color information of the point can be provided as data obtained by quantizing information of red (R), green

20   (G) and blue (B) at the address into 8 bits, for example.
       The coordinates $(x_{i,j}, y_{i,j})$ of the corresponding point $G_{i,j}$ in the three-dimensional virtual space are in a one-to-one correspondence

25   with the digital image coordinate system (u, v). For example, the relationship shown in the equation 53 holds true.
       [Equation 53]

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} k_u & -k_u \cot\theta & u_0 \\ 0 & k_v / \sin\theta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

30   In the equation 53, the u axis of the digital image coordinate system is set parallel to the x axis. In addition, in the equation 53, k_u and k_v respectively represent unit lengths of the u axis and the v axis

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of the digital image coordinate system with respect to the (x,y) coordinate system on the virtual space, and θ indicates an angle formed between the u axis and the v axis.

5   Thus, in the step 303, the coordinates (X_j, Y_j, Z_j) of the projection point T_j are associated with the digital image coordinates (u_{ij}, v_{ij}). The establishment of the association may be performed by providing values of (X_j, Y_j, Z_j) in a table for every

10   (u_{ij}, v_{ij}), or by setting values of (X_j, Y_j, Z_j) only for representative values of (u_{ij}, v_{ij}) so as to obtain other points by performing interpolation processing such as linear interpolation, for example.

       In addition, although (u,v) take discrete

15   values in the digital image coordinate system, it is assumed that (u,v) take continuous values unless otherwise specified in the following descriptions, and it is assumed to perform proper discretization processing when accessing the two-dimensional array.

20   Next, after performing processing of the step 303, groups (camera set) Ξ_h of viewpoints C_i of the cameras used for obtaining the correlation degree Q_j is determined (step 304). When the viewpoints C_i, that is, the cameras are placed like

25   a 3×3 lattice as shown in Fig.32, for example, four camera sets Ξ_h are determined as $\Xi_1 = \{C_1, C_2, C_3, C_5\}$, $\Xi_2 = \{C_3, C_5, C_6, C_9\}$, $\Xi_3 = \{C_5, C_7, C_8, C_9\}$ and $\Xi_4 = \{C_1, C_4, C_5, C_7\}$.

       Any method can be adopted as the method for determining the camera sets Ξ_h. In the example shown in Fig.32, the sets are not limited to the

30   shown in Fig.32, the sets are not limited to the four sets Ξ_1, Ξ_2, Ξ_3 and Ξ_4, so that other camera sets may be provided. In addition, the camera sets Ξ_h may be provided beforehand according to the placement status of the cameras (viewpoints C_i), or

35   may be specified by the observer.

       Next, after performing the processing of the step 304, an array is kept, in a memory (storing

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means) of the image generation apparatus, for
storing information of the color information K_j of
the projection point T_j and the probability β_j that
the object exists (step 305). As to the array for
5   storing the information, an array is kept such that
8 bits are assigned for each pieces of information
K_j and β_j at the projection point T_j that are color
information of red (R), green (G) and blue (B) and
the probability that the object exists.

10   Next, after performing the processing of
the step 305, the color information and the
probability that the object exists at each
projection point T_j are determined using the
obtained plural images (step 306). In the step 306,
15   for a projection point series, processing is
performed for obtaining the color information $K_{j,h}$
and the correlation degree $Q_{j,h}$ at each projection
point T_j on the projection point series using the
specified camera set Ξ_h. Then, the processing is
20   repeated for every camera set Ξ_h. Then, the
repeating processing is repeated for every
projection point series. Thus, in the step 306, the
projection point series is initialized as shown in
Fig.30, first (step 30601).

25   Next, the camera set Ξ_h and voting data of
correlation degree are initialized (step 30602).

         Next, the projection point T_j on the
projection point series to be processed is
initialized to j=1, for example (step 30603).

30   Next, the color information $K_{j,h}$ of the
projection point T_j is determined based on the color
information of the corresponding points $G_{i,j}$ included
in the selected camera set Ξ_h (step 30604). At this
time, color information $K_{j,h}$ of the projection point
35   T_j is determined as an average of color information
$K_{i,j}$ of the corresponding points $G_{i,j}$ included in the
camera set Ξ_h, for example.

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Next, the correlation degree $Q_{j,h}$ of the
corresponding points $G_{i,j}$ included in the selected
camera set Ξ_h is calculated (30605). At this time,
the correlation degree $Q_{j,h}$ is calculated using the
5   equation 40, for example.

Next, the projection point T_j is updated,
and it is determined whether processing of the steps
30604 and 30605 is performed for every projection
point on the projection point series to be processed
10   (step 30606). When a projection point on which the
processing of the steps 30604 and 30605 has not been
performed remains, the processing is repeated by
returning to the step 30604.

After the processing of the steps 30604
15   and 30605 is performed for every projection point on
the projection point series to be processed, the
results, that is, the color information $K_{j,h}$ and the
correlation degree $Q_{j,h}$ obtained from the
corresponding points $G_{i,j}$ included in the selected
20   camera set Ξ_h are voted (step 30607).

Next, after completing the processing of
the step 30607, the camera set Ξ_h is updated, and it
is determined whether there is a camera set for
which processing of steps 30604-30607 has not been
25   performed for the projection point series to be
processed (step 30608). When there is a camera set
for which processing of steps 30604-30607 has not
been performed, the processing is repeated by
returning to the step 30603.

30   After performing the processing of steps
30604-30607 for every camera set Ξ_h for the
projection point series to be processed, the color
information K_j and the existence probability β_j of
the projection points T_j are determined from the
35   color information $K_{j,h}$ and the correlation degree $Q_{j,h}$
that are voted at the step 30607 (step 30609).

In the step 30609, the camera set Ξ_h is

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initialized first as shown in Fig.31, for example (step 30609a).

Next, the evaluation reference value $\nu_{j,h}$ is calculated from the correlation degree $Q_{j,h}$ of each projection point T_j calculated using the camera set Ξ_h (step 30609b). The evaluation reference value $\nu_{j,h}$ is obtained by performing conversion processing represented by the equation 43 and the equation 44, for example.

Next, statistical processing for the evaluation reference value $\nu_{j,h}$ is performed, so that the distribution function $p_h(l)$ of the existence probability when the camera set Ξ_h is used is obtained (step 30609c). The distribution function $p_h(l)$ is obtained using the equation 45, the equation 46 and the equation 47, for example.

Next, based on the distribution function $p_h(l)$ of the existence probability in the case when the camera set Ξ_h is used, the probability (existence probability) $\beta_{j,h}$ that the surface of the object exits on each projection point T_j is determined (step 30609d). The existence probability $\beta_{j,h}$ is determined using the equation 48, the equation 49 and the equation 50, for example.

Next, the camera set Ξ_h is updated, and it is determined whether there is a camera set Ξ for which processing from the step 30609b to the step 30609d has not been performed (step 30609e). When there is a camera set Ξ for which processing from the step 30609b to the step 30609d has not been performed, the processing is repeated by returning to the step 30609b.

After performing the processing from the step 30609b to the step 30609d for the projection point series to be processed, the processing results are integrated so that the color information K_j and the existence probability β_j at the projection point

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T_j are determined (step 30609f). At this time, the color information K_j is obtained using the equation 52, for example. The existence probability β_j is obtained using the equation 51, for example.

5   After completing the processing of the step 30609f, the processing of the step 30609 completes. Then, next, the projection point series is updated, and it is determined whether there is projection point series for which processing from

10   the step 30602 to the step 30609 has not been performed (step 30610). When there is projection point series for which processing from the step 30602 to the step 30609 has not been performed, the processing is repeated by returning to the step

15   30602.

After performing processing from the step 30602 to the step 30609 for every projection point series, processing of the step 306 (step 3) completes so that the three-dimensional shape of the

20   object can be obtained.

Next, after the processing of the step 3 completes and the three-dimensional shape of the object is obtained, two-dimensional images to be displayed on each image display plane of the DFD are

25   generated based on the three-dimensional shape of the object. For generating the two-dimensional image, image generation planes $LD_r (r=1,2,…,R)$ for generating the two-dimensional images are set on the virtual space from which the shape of the object is

30   obtained as shown in Fig.33, for example.

First, a case is considered in which the setting number of the projection planes L_j and the intervals are the same as the number of the image generation planes LD_r and the intervals respectively.

35   In this case, the color information KD_h and the existence probability Y_r at a display point A_r on the image generation plane LD_r are determined to be the

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color information K_j and the existence probability β_j at the projection point T_j the same as the display point A_r.

5　The setting intervals of the projection planes L_j are not necessarily the same as the placement intervals of the image generation planes LD_r, and the setting number of the projection planes L_j is not necessarily the same as the setting number of the image generation planes LD_r. That is,

10　according to the setting method of the projection planes L_j, there is a case where the setting intervals of the projection planes L_j are not the same as the placement intervals of the image generation planes LD_r as shown in Fig.34A, for

15　example. In such a case, the color information KD_r and the existence probability γ_r at the cross points (display point) A_r of the line lr extending from the observer's viewpoint P and each image generation surface LD_r are obtained according to the following

20　procedure.

First, the color information KD_r at each display point A_r is determined to be an average value of color information K of projection points T, that is the projection points T_j on the line lp, for

25　which the display point A_r (image generation plane LD_r) becomes the nearest display point (image generation plane). Instead of the average value, the color information KD_r at the display point A_r may be determined as color information K of a projection

30　point T nearest to the display point A_r.

On the other hand, the existence probability of the display point A_r is determined as a value obtained by adding existence probabilities β of projection points T for which the display point

35　A_r (image generation plane LD_r) becomes the nearest display point (image generation plane). Assuming that a set of projection planes L_j for which an

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image generation plane LD_r becomes the nearest image
generation plane is $\{L_j | j \in R\}$, the existence
probability γ_h of the display point A_r on the image
generation plane LD_r can be obtained by the

5   following equation 54 using the existence
probability β_j of the projection points T_j of each
projection plane L_j.

[Equation 54]

$$\gamma_h = \sum_{j \in J} \beta_j$$

10   Considering the case shown in Fig.34A, the image
generation plane LD_1 becomes the nearest image
generation plane for the projection planes L_1, L_2
and L_3. Therefore, the color information KD_r of the
display point A_r is determined to be an average

15   value of the pieces of color information K_1, K_2 and
K_3 of the projection points T_1, T_2 and T_3, for
example. In addition, the existence probability γ_r
of the display point A_r is determined to be a sum of
the existence probabilities β_1, β_2 and β_3 of the

20   projection points T_1, T_2 and T_3, for example. In the
same way, the color information KD_2 of the display
point A_2 on the image generation plane LD_2 is
determined to be an average value of the pieces of
color information K_4 and K_5 of the projection points

25   T_4 and T_5, for example. In addition, the existence
probability γ_2 of the display point A_2 is determined
to be a sum of the existence probabilities β_4 and β_5
of the projection points T_4 and T_5, for example.

In addition, for example, when the setting

30   intervals of the image generation planes D_r are not
the same as the setting intervals of the projection
planes L_j so that two projection planes L_1 and L_2 are
set between two successive image generation planes
LD_1 and LD_2 as shown in Fig.34B, for example, the

35   existence probability γ_1, γ_2 of the display point A_1,

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A$_2$ of the image generation plane LD$_1$, LD$_2$ may be obtaining by distributing the existence probability β$_j$ of the projection point T$_j$ of the projection plane L$_j$ according to the ratio of distance to each image generation plane LD$_1$, LD$_2$. Generally, assuming that a set of plural projection planes L$_j$ between the image generation planes LD$_1$ and LD$_2$ is {L$_j$|j∈J}, the existence probability γ$_r$ of the display point A$_r$ on the image generation plane LD$_r$ can be supplied by the following equation 55 using the existence probability β$_j$ of each projection point T$_j$.

[Equation 55]

$$\gamma_h = \sum_{j \in J} w_{j,r}\, \beta_j$$

wherein w$_{j,r}$ indicates a coefficient representing a degree of contribution of the projection plane L$_j$ to the image generation plane LD$_r$.

Here, it is considered that projection planes L$_1$ and L$_2$ are set between the two image generation planes LD$_1$ and LD$_2$ as shown in Fig.34B. At this time, when the distances from the projection plane L$_1$ to each of the image generation planes LD$_1$ and LD$_2$ are B$_1$ and B$_2$ respectively, the degrees w$_{1,1}$ and w$_{1,2}$ of contribution of the projection plane L$_1$ to the image generation planes LD$_1$ and LD$_2$ are provided respectively by the following equation 56.

[Equation 56]

$$w_{1,1} = \frac{B_2}{B_1 + B_2}, \quad w_{1,2} = \frac{B_1}{B_1 + B_2}$$

In the same way, when the distances from the projection plane L$_2$ to each of the image generation planes LD$_1$ and LD$_2$ are B$_3$ and B$_4$ respectively, the degrees w$_{2,1}$ and w$_{2,2}$ of contribution of the projection plane L$_2$ to the image generation surfaces

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LD$_1$ and LD$_2$ are provided respectively by the following equation 57.

[Equation 57]

$$w_{2,1} = \frac{B_4}{B_3 + B_4}, \quad w_{2,2} = \frac{B_3}{B_3 + B_4}$$

5   As a result, the existence probability γ_1 of the display point A$_1$ of the image generation plane LD$_1$ and the existence probability γ_2 of the display point A$_2$ of the image generation plane LD$_2$ can be supplied respectively by the following
10   equation 58.

[Equation 58]

$$\gamma_1 = w_{1,1}\,\beta_1 + w_{2,1}\,\beta_2, \quad \gamma_2 = w_{1,2}\,\beta_1 + w_{2,2}\,\beta_2$$

According to the above-mentioned procedure, by performing the processing of the step 4, the two-
15   dimensional images to be displayed on each image display plane of the DFD can be obtained. Then, each point (pixel) on each image display plane of the DFD is displayed with color information A that is assigned to each point on each image generation
20   plane LD (step 5). At this time, when the DFD is the brightness modulation type, color information KD$_r$ of each display point A$_r$ of each image generation plane LD$_r$ is displayed with brightness according to the existence probability γ_r. When the DFD is the
25   transmission type, transparency of each display point A$_r$ is set to transparency according to the existence probability γ_r and it is displayed.

Accordingly, by performing the processing from the step 1 to the step 5 shown in Fig.29 so as
30   to display the three-dimensional image of the object on the DFD, a three-dimensional image that looks natural for the observer can be displayed without obtaining the accurate three-dimensional shape of the object as described in the principle.

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Figs.35-37 are schematic diagrams showing general configurations of an apparatus and a system to which the image generation method of this embodiment 2-1 is applied. Fig.35 is a block
5   diagram showing a configuration example of the image generation apparatus. Fig.36 is a diagram showing a configuration example of an image display system using the image generation apparatus. Fig.37 is a diagram showing another configuration example of the
10 image display system using the image generation apparatus.

In Fig.35, 6 indicates the image generation apparatus, 601 indicates an object image obtaining means, 602 indicates a reference viewpoint
15 setting means, 603 indicates a projection plane setting means, 604 indicates a projection plane information storing area keeping means, 605 indicates a color information/existence probability determination means, 606 indicates a projection
20 plane information – display plane information conversion means, 607 indicates an image output means, 7 indicates an image display means (DFD), 8 indicates an object image taking means, and 9 indicates an observer viewpoint input means.

25 As shown in Fig.35, for example, the image generation apparatus 6 to which the image generation method of this embodiment 2-1 is applied includes the object image obtaining means 601 for obtaining plural object images taken under different
30 photographing conditions, the reference viewpoint setting means 602 for setting a viewpoint of the observer who observes a generated image, the projection plane setting means 603 for setting projection planes, projection point series,
35 projection points, camera sets and the like for determining the existence probability, the projection plane information storing area keeping

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means 604 for keeping an area for storing color information and existence probability of points (projection points) on the projection plane, the color information/existence probability

5 determination means 605 for determining the color information of the projection points and the probability (existence probability) that the object exist at the projection points, the projection plane information - display plane information conversion

10 means 606 for converting the color information and the existence probability information of the projection point to color information and existence probability of the display plane, and the image output means 607. An image output from the image

15 output means 607 is displayed by the image display means 7 such as the DFD including plural overlapping display planes.

     The object image obtaining means 601 obtains images of the object taken by the object

20 image taking means (camera) 8. The image to be obtained may be one directly obtained from the image taken by the object image taking means 8, or may be indirectly obtained from a recording medium that is magnetic, electrical or optical that stores the

25 image taken by the object image taking means 8.

     The observer viewpoint setting means 602 sets relative position relationship between the observer's viewpoint P and the image generation planes LD_r such as distance from the viewpoint P to

30 the image display means 7 and the line of sight based on information that is input by the observer using the image condition input means 9 such as the mouse or a keyboard, for example. The image condition input means 9 may be a means for detecting

35 posture or line of sight of the observer so as to input information according to the posture or the line of sight.

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The projection plane etc. setting means 603 sets parallel projection planes L_j in which the distances from the projection planes L_j from the viewpoint (camera) C_i are l_j ($j=1,2,…,M$). In addition,

5   the projection plane setting means 603 also sets projection point series each being a group of projection points T_j on each projection plane L_j overlapping when viewed from the observer's viewpoint P set by the observer viewpoint setting

10   means 602, and the corresponding points $G_{i,j}$, on each image, corresponding to the projection point T_j. In addition, the projection plane setting means 603 may set camera sets Ξ_h based on the condition input by the image condition input means 9.

15   The projection plane information storing area keeping means 604 keeps the area for the color information K_j and the existence probability β_j of each projection point T_j on each projection plane in a memory provided in the apparatus, for example.

20   The color information/existence probability determination means 605 determines the color information K_j of the projection point T_j from color information of corresponding points G_{ij} on the images corresponding to the projection point T_j, and

25   determines the probability β_j that the surface of the object exists on the projection point T_j based on the before-mentioned principle.

The projection plane information – display plane information conversion means 606 converts the

30   color information and the existence probability of the projection plane into color information and the brightness distribution ratio of a point on the plane on which the image to be displayed on the display plane of the image display means 7 is

35   generated, that is, converts the color information and the existence probability of the projection plane into color information and the brightness

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distribution ratio of a point on the image generation plane.

The image generation apparatus 6 performs processing from the step 1 to the step 5 described
5 in this embodiment 2-1 to generate the image to be displayed on the DFD. That is, it is not necessary for the image generation apparatus 6 to perform processing for obtaining an accurate three-dimensional shape of the object as conventionally
10 performed. Therefore, even by an apparatus that does not have high processing ability, the images to be displayed on the DFD can be generated easily and at high speed.

The image generation apparatus 6 can be
15 also realized by a computer and a program executed by the computer, for example. In such as case, a program that describes instructions corresponding to the processing procedure described in this embodiment 2-1 is executed on the computer. In
20 addition, the program can be provided by storing in a recording medium that is magnetic, electrical or optical, or can be provided via a network such as the Internet.

In addition, the image display system
25 using the image generation apparatus 6 can be considered to be configured as shown in Fig.36, for example. In the configuration, the object image taking means 8 may be placed at a place near the space where the observer User observes the image
30 display means (DFD) 7, or may be placed at a place geographically apart. When the object image taking means 8 is placed at the geographically apart place, the taken images can be transferred to the image generation apparatus 6 using a network such as the
35 Internet.

In addition, as shown in Fig.36, the image display system using the image generation apparatus

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6 can be applied not only to a case where an observer User observes an object Obj but also to a bi-directional communication system such as TV phone and TV conference. In the case, spaces in which the
5   observers UserA and UserB exist are respectively provided with image generation apparatuses 6A and 6B, image display means (DFDs) 7A and 7B, object image taking means 8A and 8B, and reference viewpoint setting means 9A and 9B as shown in Fig.37, for
10   example. Then, for example, by connecting between the image generation apparatuses placed at the spaces where the observers UserA and UserB exist by the network 10 such as the Internet, the observer UserA can observe, by the image display means 7A,
15   the three-dimensional image of the observer UserB generated from the images taken by the object image taking means 8B. In the same way, the observer UserB can observe, by the image display means 7B, the three-dimensional image of the observer UserA
20   generated from the images taken by the object image taking means 8A.
         In addition, for applying the image generation apparatuses to such bi-directional communication system, it is not necessary that both
25   of the image generation apparatuses 6A and 6B are configured as those shown in Fig.35. Either one of the image generation apparatuses 6A and 6B can be a general communication terminal that does not include the configuration means shown in Fig.35. In
30   addition, each configuration means shown in Fig.35 may be distributed to the image generation apparatuses 6A and 6B.
         In addition, as shown in Fig.37, if another image generation apparatus 6C is provided on
35   the network 10, the three-dimensional image of the object to be displayed on the image display means (DFD) 7A and 7B can be obtained using the image

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generation apparatus 6C on the network 10 even when
the image generation apparatuses 6A and 6B are not
placed at the spaces where the observers UserA and
UserB exists.

5   In addition, in the image generation
system shown in Fig.37, although the number of the
users UserA and UserB are two, the image generation
scheme can be applied to a communication system
among more observers (users).

10   In addition, although Figs.36 and 37 show
that the object image taking means includes four
cameras, the number of the cameras may be two or
three or more than four. In addition, the cameras
may be placed one-dimensionally on a line or a curve,

15   or placed like a two-dimensional lattice on a plane
or a curved surface.

As described above, according to the image
generation method of this embodiment 2-1, the three-
dimensional image that looks natural for the

20   observer can be displayed without obtaining an
accurate three-dimensional shape of the object to be
displayed.

In addition, in the image generation
method of this embodiment 2-1, although processing

25   is performed by setting the camera sets Ξ_h in step
304 beforehand, the processing is not limited to
this way. The camera sets may be dynamically set by
software processing such that the sets matches
conditions specified by the observer while

30   performing processing for generating the images to
be displayed, for example. In this case, by
inputting the conditions such as distribution or
threshold of the correlation degree Q_j from the
image condition input means by the observer and by

35   performing processing of the step 306 while
searching for camera sets that match the conditions,
it can be considered that the three-dimensional

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image close to an image desired by the observer can
be displayed.

In addition, in the image generation
method of this embodiment 2-1, although a case is
5   described as an example in which a color image in
which the point (pixel) is represented by color
information using three primary color of red (R),
green (G) and blue (B) is obtained and the three-
dimensional shape of the object is generated, the
10   image to be obtained is not limited to the color
image. In the image generation method of this
embodiment 2-1, a black and white image in which the
point (pixel) is represented by brightness (Y) and
color-difference (U,V) may be obtained so as to
15   obtain the three-dimensional shape of the object.
In the case when the image to be obtained is the
black and white image, the three-dimensional shape
can be obtained, by the procedure described in this
embodiment 2-1, using brightness information (Y) as
20   information corresponding to the color information
so that the two-dimensional images can be generated.
(Embodiment 2-2)

Fig.38-42 are block diagrams for
explaining an arbitrary viewpoint image generation
25   method of the embodiment 2-2. Fig.38 is a flow
diagram showing an example of the whole processing
procedure. Fig.39 is a diagram for explaining a
principle of rendering. Fig.40 is a diagram for
explaining problems that arise when generating the
30   arbitrary viewpoint image. Figs.41A and B are
diagrams for explaining a method for solving the
problems that arise when generating the arbitrary
viewpoint image. Fig.42 is a flow diagram showing
an example of the processing procedure for
35   converting the existence probability to transparency.

In the embodiment 2-1, although a method
for generating the two-dimensional images to be

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displayed on each image display plane of the.
apparatus having plural image display planes like
the DFD using the three-dimensional shape of the
object obtained in the step 3 is taken as an example,
5   the three-dimensional shape of the object is not
limited to that, but it can be also used for
generating two-dimensional images of the object
viewed from arbitrary viewpoints. In this case, the
difference compared to the embodiment 2-1 is that
10   rendering is performed after the step 3, that is,
processing of step 11 for generating the two-
dimensional images of the object viewed from the
observer's viewpoint based on the three-dimensional
shape. Since the processing from the step 1 to the
15   step 3 in which the three-dimensional shape of the
object is obtained is the same as that described in
the embodiment 2-1, it is not described in detail.
        In the step 11 for rendering in the
arbitrary viewpoint image generation method of this
20   embodiment 2-2, the color information of each point
(pixel) on the arbitrary viewpoint image to be
displayed is determined by performing mixing
processing for color information K_j of projection
points $T_j(j=1,2,…,M)$ overlapping with a point A on
25   the arbitrary viewpoint image as shown in Fig.39,
for example. In the mixing processing, for example,
weight that is the existence probability β_j is
assigned to color information K_j of each projection
point T_j, and weighted color information K_j are mixed,
30   so that the color information K_A of the point on the
image to be generated is calculated by the following
equation 59, for example.
   [Equation 59]

$$K_A = \sum_{j=1}^{M} \beta_j K_j$$

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However, according to mixing processing using the
equation 59, the color information of the point of
the image may be far different from the color
information of the actual surface of the object or
5   may be not fall within an effective color space
depending on the shape of the object or position
relationship between the reference viewpoint R and
the virtual viewpoint P, for example. Here, a case
is considered in which two projection planes L_1 and
10   L_2, a reference viewpoint R and a virtual viewpoint
P are applied for an actual object in position
relationship as shown in Fig.40. In this case, when
existence probabilities β_1 and β_2 are determined with
respect to the projection points T_1 and T_2
15   overlapping when viewed from the reference viewpoint
R by the method described in the embodiment 2-1, β_1
becomes almost 0 and β_2 becomes almost 1. Similarly,
when existence probabilities β'_1 and β'_2 are
determined with respect to the projection points T'_1
20   and T'_2 overlapping when viewed from the reference
viewpoint R by the method described in the
embodiment 2-1, β'_1 becomes almost 1 and β'_2 becomes
almost 0.
        The color information K_A at the point A of
25   the image plane of the virtual viewpoint P is
obtained by adding, after assigning weights
according to the existence probabilities β'_1 and β_2,
color information K'_1 and K_2 of the projection points
T'_1 and T_2 overlapping with the point A on the image
30   plane when viewed from the virtual viewpoint P. By
doing so, both of them become almost 1, so that the
color information K_A of the point A becomes $K_A=K'_1+K_2$.
        However, when the object Obj is viewed
from the virtual viewpoint P, since the projection
35   point T'_1 is blocked by the projection point T_2,
actual color information at the point A on the image
plane should be $K_A=K_2$. That is, brightness of each

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component (R,G,B) of the generated color information K_A at the point A on the image is increased by K'_1 compared with the actual color information.

     In addition, when each component of the
5   color information K'_1 and K_2 of the projection points T'_1 and T_2 has large brightness, the color information K_A of the point A exceeds a limit of an effective color space. Therefore, clipping processing is necessary for the color information to
10 fall within the limit of the effective color space.

     To solve the problem, transparency that may take plural gradations from transparent to opaque is provided to each projection point based on the existence probability of the projection point.
15 In this case, the mixing processing is performed successively from a projection point of the generated image far from the viewpoint to a projection point near the viewpoint, in which color information obtained by the mixing processing up to
20 a projection point is obtained by performing interior division between color information at the projection point and color information obtained by mixing processing up to a previous projection point with a ratio according to the transparency. The
25 color information obtained by the mixing processing is interior division between color information at a stage and color information at the next stage.

     For explaining the principle of the mixing processing of the color information, assuming a case
30 in which projection planes L_j ($j=1,2,…,M$), projection points T_j, and a vector K_j having components of red (R), green (G) and blue (B) and representing color information of the projection point are set in a color space V as shown in Fig.41A, for example. It
35 is assumed that the color space V is represented by the following equation 60.

  [Equation 60]

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$$K_j \in V, V \equiv \left\{ (R, G, B) \middle| 0 \le R \le 1, \ 0 \le G \le 1, \ 0 \le B \le 1 \right\}$$

In addition, it is assumed that the transparency α_j of the projection point T_j is set so as to satisfy a

5　condition shown in the following equation 61.
　　[Equation 61]

$$0 \le \alpha_j \le 1$$

The color information D_m obtained by mixing processing up to the argument j=m is represented by

10　recurrence formulas shown in equations 62 and 63. Then, color information D_M of the projection plane L_M nearest to the virtual viewpoint P, that is, color information D_M obtained by performing mixing processing up to the argument j=M becomes the color

15　information K_A at the point A on the image plane of the image to be generated.
　　[Equation 62]

$$D_m = \alpha_m K_m + \left(1 - \alpha_m \right) D_{m-1}$$

　　[Equation 63]

20
$$D_1 = \alpha_1 K_1$$

In addition, as shown by the relationship of the equations 61 and 62, the color information D_m is a internally divided point between the vector K_m and the color information D_{m-1} in the color space V as

25　shown in Fig.41B.　Therefore, as to the color information D_m, when $K_m \in V$ and $D_{m-1} \in V$ are satisfied, $D_m \in V$ holds true.
　　　　Then, as described in the first embodiment, when the conditions of the equations 60 and 61 are

30　satisfied, $D_M \in V$ is ensured with respect to the color information D_M at the virtual viewpoint P.
　　　　That is, by setting the color information K_j and the transparency α_j at the projection point T_j

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so as to satisfy the equations 60 and 61, the color
information D_M of the point A of the image to be
generated can always fall within a proper color
space V.

5   As mentioned above, for generating images
obtained by viewing the same object from plural
virtual viewpoints, by performing the mixing
processing of the color information using the
transparency α_j, all images can be generated within
10   a limit of proper color information even when
calculating the color information and the
transparency of the projection point from a
viewpoint (reference viewpoint) if the color
information and the transparency satisfies the
15   equations 60 and 61.

         Therefore, according to a generation
method of the arbitrary viewpoint image of this
embodiment 2-2, processing for converting the
existence probability β_j to the transparency α_j is
20   performed after the step 30609 shown in Fig.30 or in
the step 11 for performing rendering.

         In the processing for converting the
existence probability β_j to the transparency α_j, the
projection point T_j is initialized to j=M first as
25   shown in Fig.42, for example (step 1101). Next, β_M
is substituted to transparency α_M of the projection
point T_M such that $\alpha_M=\beta_M$ (step 1102).

         Next, the value of the argument j is
updated to j=j-1 (step 1103). Then, it is
30   determined whether the transparency α_{j+1} is 1 (step
1104). If transparency $\alpha_{j+1}\neq 1$, the transparency α_j
is obtained from the equation 64, for example (step
1105).

   [Equation 64]

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$$\alpha_j = \frac{1}{\displaystyle\prod_{m=j+1}^{M}(1-\alpha_m)}\beta_j$$

If the transparency α_{j+1} is 1, 1 is substituted into α_j ($\alpha_j=1$), for example (step 1106). When obtaining the transparency α_j in the step 1105, the equation

5   is not limited to the equation 64, and other equations can be used. In addition, although detailed descriptions are not provided, since any value can be substituted into the transparency α_j actually in step 1106, a value other than 1 may be

10   substituted into the transparency α_j.
          Next, it is determined whether processing from the step 1104 to the step 1106 has been performed up to the argument j=1 (step 1107). When the processing has not been performed, the

15   processing is repeated after returning to the step 1103.
          After performing the processing from the step 1104 to the step 1106 up to the argument j=1, processing for converting the existence probability

20   β_j of the projection point T_j overlapping with the point A, on the image plane, viewed from the observer's viewpoint P into the transparency α_j completes. After that, mixing processing using the equation 62 and the equation 63 is performed. Then,

25   by performing the processing for every point (pixel) on the arbitrary viewpoint image, the arbitrary viewpoint image from the observer's viewpoint P can be obtained.
          The basic configuration of the image

30   generation apparatus for generating such arbitrary viewpoint image is the same as that of the image generation apparatus described in the embodiment 2-1. As a means corresponding to the projection plane

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information – display plane information conversion
means 606 shown in Fig.35, a means for performing
before-mentioned mixing processing may be provided.
Thus, descriptions on the apparatus are not provided.

5   As described above, according to the image
generation method of this embodiment 2-2, the three-
dimensional image that looks natural for the
observer can be displayed without obtaining an
accurate three-dimensional shape of the object to be
10   displayed.

In addition, also in the image generation
method of this embodiment 2-2, the camera sets Ξ_h
may be dynamically set by programmatic processing
such that the sets match conditions specified by
15   the observer while performing processing for
generating the image to be displayed, for example.
In this case, by inputting the conditions such as
distribution or threshold of the correlation degree
Q_j from the image condition input means by the
20   observer and by performing processing of the step
306 while searching for camera sets that match the
condition, it can be considered that the three-
dimensional image close to an image desired by the
observer can be displayed.

25   In addition, also in the image generation
method of this embodiment 2-2, as to the image to be
obtained, either of the color image or the black and
white image can be adopted. In the case when the
image to be obtained is the black and white image,
30   after the three-dimensional shape is obtained by the
procedure described in the embodiment 2-1 using the
brightness information (Y) as information
corresponding to the color information, the virtual
viewpoint image can be generated according to the
35   procedure described in this embodiment 2-2.

(Effects of the second embodiment)

As mentioned above, according to the image

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generation method of the second embodiment, when
obtaining the three-dimensional shape of the object,
plural projection planes are set, and the
probability (existence probability) that the surface
5   of the object exists is provided for the points
(projection point) of each projection plane
overlapping viewed from the reference viewpoint.
That is, the method does not intend to obtain an
accurate three-dimensional shape of the object
10 assuming that the surface of the object exists on a
projection plane among projection points overlapping
viewed from the reference viewpoint, as
conventionally performed, but the three-dimensional
shape of the object is obtained assuming that the
15 surface of the object exists on each projection
point with an existence probability. Accordingly,
when estimating a distance of the surface of the
object in a direction from the reference viewpoint,
a portion in which the estimation reliability is low
20 is rendered vaguely in a ratio according to the
existence probability of each projection point.
Therefore, when generating the image based on the
three-dimensional shape of the object, discontinuous
noise that appears when the estimation of the
25 distance of the object surface includes an error,
that occurs in a conventional technology, can be
made inconspicuous, so that an image that looks
natural can be generated.
          In addition, as mentioned before, when the
30 object surface near a projection point does not
appear from a viewpoint of an area due to an effect
of the occlusion when calculating the existence
probability based on plural images included in the
camera sets from obtained images, existence
35 probability in which the image taken from the
viewpoint is excluded can be calculated so that the
reliability of the existence probability of each

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projection point increases.

In addition, when determining the existence probability, if the probability density distribution of the existence probability can be

5   estimated to some extent, the evaluation reference value may be calculated from the correlation degree of each projection point so as to determine the existence probability based on the distribution function obtained by performing statistical

10   processing on the evaluation reference value. Accordingly, by determining the existence probability by performing the statistical processing, deterioration of the reliability due to the noise on the obtained images can be prevented.

15   [Third embodiment]

Next, the third embodiment of the present invention is described. The third embodiment is an embodiment mainly corresponding to claims 22-29. In the third embodiment, based on plural images (multi-

20   focus image) taken by changing focusing distance from one viewpoint, the three-dimensional shape of the object appearing in the images is obtained, so that the image of the object viewed from an arbitrary viewpoint (virtual viewpoint) is generated.

25   That is, compared to the first and second embodiments in which the three-dimensional shape of the object is obtained based on plural images of the object taken from plural viewpoints, this embodiment is characterized by using plural images taken by

30   changing focusing distance from one viewpoint. Also in this embodiment, the three-dimensional shape of the object is represented by the multi-layered planes using the texture mapping method. In figures for explaining the third embodiment, the same

35   reference numerals are assigned to components having the same function.

Figs.43-51 are schematic diagrams for

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explaining the principal of the image generation
method of this embodiment. Figs.43 and 44 are
diagrams showing a setting example of the projection
planes and the reference viewpoint. Fig.45 is a
5   diagram for explaining a method for determining the
color information and the focusing degree of the
projection point. Figs.46-48 are diagrams for
explaining a method of determining the existence
probability of the projection point. Fig.49 is a
10   diagram for explaining a method for generating an
image viewed from the virtual viewpoint. Fig.50 is
a diagram for explaining problems in the image
generation method in this embodiment. Fig.51 is a
diagram for explaining a method for solving the
15   problems in the image generation method in this
embodiment.
        In the image generation method of this
invention, as mentioned before, based on plural
images (multi-focus image) taken by changing
20   focusing distance from one viewpoint, the three-
dimensional shape of the object appearing in the
images is obtained so that an image of the object
viewed from an arbitrary viewpoint (virtual
viewpoint) is generated. In this method, the three-
25   dimensional shape of the object is represented by
multi-layered planes using the texture mapping
method.
        For representing the three-dimensional
shape of the object using the texture mapping method,
30   the viewpoint C of the camera, projection planes
L_j (i=1,2,…,M) of the multi-layered structure and the
reference viewpoint R for obtaining the three-
dimensional shape of the object are set in a virtual
three-dimensional space set in the image generation
35   apparatus such as a computer as shown in Fig.43, for
example. Assuming that the shape of the object is
obtained from N images of different focusing

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distances, the projection planes L_j are set at each distance the same as the focusing distance f_i of each image $Img_i (i=1,2,…,N)$ as shown in Fig.44.

      As shown in Fig.44, considering projection
5 points $T_j (j=1,2,…,N)$ overlapping when viewed from the reference viewpoint R in a direction, the surface of the object is considered to exist at a point in the projection points T_j according to a conventional model obtaining method. The projection
10 point, among the projection points T_j, at which the surface of the object exists is determined based on the focusing degree of each of the projection points T_j, for example. Then, first, color information K_j and focusing degrees Q_j of each of the projection
15 points T_j overlapping viewed from the reference viewpoint R are determined.

      The color information K_j and focusing degrees Q_j of the projection points T_j are determined based on the color information K_i of the point
20 (corresponding point) G_i, on each image Img_i, corresponding to the projection point T_j, and the degree (focusing degree) by which focus is achieved at the corresponding point G_i. The color information K_j of the projection point T_j is
25 determined to be an average value of the color information K_i of the corresponding points G_i, or determined to be color information $K_{i=j}$ that spatially matches with the corresponding point G_{i-j}. The focusing degree of the projection point T_j can
30 be determined according to sharpness or blurriness at a point or a small region on the image. As a calculation method for the focusing degree, there are various methods based on Depth from Focus theory or Depth from Defocus theory. Following documents
35 can be referred to as for the Depth from Focus theory and the Depth from Defocus theory.

      Document 8: A.P.Pentland: "A New Sense for Depth

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of Field," IEEE Trans. On Pattern Analysis and Machine Intelligence, Vol.PAMI-9, No.4, pp.523-531(1987).

Document 9: :Murali Subbarao and gopal Surya: "Depth from Defocus: A Spatial Domain Approach," International Journal of Computer Vision, 13, 3, pp.271-294, Kluwer Academic Publishers.

Document 10: Mitsuhiro Ishihara, Hiromi Sasaki,:"High speed three-dimensional shape measurement by Focusing method", Precision Engineering, Vol.63, No.1, pp.124-128, The Japan Society for Precision Engineering.

Document 11, Koutarou Ooba, Shigeru Yamada: "Real time all focusing microscope camera", O plus E, Vol.22, No.12, pp.1568-1576, 2000, Shin Gijyutu communications.

The focusing degree Q_j can be obtained by comparing sizes of local spatial frequency of each corresponding point G_i, for example.

The Depth from Focus theory or the Depth from Defocus theory is a method for analyzing plural images having different focusing distance so as to measure the surface shape of the object. In the method, the surface of the object is estimated to exist at a distance corresponding to a focusing distance of an image having the highest local spatial frequency among the images taken by changing the focusing distance, for example. Thus, the focusing degree Q_j of the projection point T_j is calculated using an evaluation function of the local spatial frequency represented by the following equation 65, for example.

[Equation 65]

$$Q = \frac{1}{D}\sum_{x=x_i}^{x_f}\sum_{y=y_i}^{y_f}\left\{\sum_{p=-L_c}^{L_c}\sum_{q=-L_r}^{L_r}\left|f(x,y)-f(x+p,y+q)\right|\right\}$$

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wherein f indicates a gray scale of a pixel, D
indicates a constant for normalization that is a
number of all pixels, (-Lc, -Lr)-(Lc, Lr) and (xi,
yi)-(xf, yf) respectively indicate small regions for
5   performing distribution evaluation and smoothing.
This processing is performed for all
projection points T_j overlapping when viewed from
the reference viewpoint R. Then, as shown in Fig.46,
after the color information and the focusing degree
10 Q_j are determined for each projection point T_j, a
distance at which the surface of the object exists
is estimated based on the focusing degree Q_j of each
projection point T_j. As to the focusing degree Q_j
of each of projection points T_j overlapping when
15 viewed from the reference viewpoint R, when only a
focusing degree Q_n of a projection point T_n is a very
high value as shown in Fig.47A, for example, it can
be estimated that the surface of the object exists
on the projection point T_n, and the reliability is
20 very high.
However, there is a case where there is no
projection point T at which the focusing degree Q
takes a distinctive large value depending on the
condition for taking the images, the shape of the
25 object or the texture of the surface of the object
as shown in Fig.47B, for example. In the example
shown in Fig.47B, for example, since the focusing
degrees Q of the projection points T_n and T_n^* are
high to some extent compared to other focusing
30 degrees Q of other projection points T, it can be
considered that the surface of the object exists at
either one of the projection points T_n and T_n^*.
However, since any of the focusing degrees Q of the
projection points T_n and T_n^* is not a distinctive
35 large value, the reliability is low when one of the
projection points is selected. In addition,
according to circumstances, an erroneous projection

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point may be selected. Then, if erroneous
estimation (selection) is performed for estimating
the projection point at which the surface of the
object exists, a large noise appears on the
5   generated image.

In such a case, for increasing the
reliability of estimation of the distance of the
surface of the object, that is, for increasing the
reliability of estimation of a projection plane on
10 which the surface of the object exists, some
contrivance to estimate the distance of the object
surface is necessary in which more images are used
by decreasing the intervals of the focusing
distances, or not only the peak position but also
15 values before and after the peak position are
applied to a known function such as normal
distribution function, for example.

However, when more images are used, there
are problems that processing time increases, and
20 that it becomes difficult to adjust the focusing
distances in the image taking means. In addition,
when focusing at a focusing distance, there is a
region called depth of field before and after the
focus. If a point is within the limit of the depth
25 of field, blurriness does not substantially occur on
the image even when the point is not at the focusing
distance. Therefore, effects can be obtained by
dividing the focusing distances into smaller
intervals as long as the interval is decreased up to
30 about the depth of field. Even if the interval is
further decreased, the effect is small. In addition,
when the spatial frequency of the texture of the
object surface is low, that is, when change of the
texture is small so that the texture is even,
35 changes are hard to occur on the image even when the
focusing distance is changed. In this case, it is
difficult to estimate with high reliability in

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principle.

Therefore, generally, even when the distribution of the focusing degree Q is as shown in Fig.47B, it is assumed that the surface of the
5   object exists at the projection point T_j where the focusing degree Q is maximum. Therefore, there are many cases where erroneous estimation for the distance of the object surface is performed so that a large noise appears on the generated image.
10   Thus, according to the image generation method of this invention, the distance of the surface of the object is not specified as one point, that is, the distance of the surface of the object is not specified as one of projection points T_j
15   overlapping when viewed from the reference viewpoint R, but existence probability β_j is provided according to the focusing degree Q_j of each projection point T_j. In this method, the existence probability β_j needs to satisfy the following
20   equation 66 and the equation 67 in a set of the existence probability β_j of all projection points T_j overlapping when viewed from the reference viewpoint R.

[Equation 66]

25
$$0 \leq \beta_j \leq 1$$

[Equation 67]

$$\sum_{j=1}^{M} \beta_j = 1$$

Then, assuming that the number of the projection planes L_j is M and that the number of the projection
30   points T_j overlapping when viewed from the reference viewpoint R is M, the existence probability β_k of the projection point T_k on a k-th projection plane L_k is obtained by the following equation 68.

[Equation 68]

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$$\beta_k = \frac{Q_k}{\displaystyle\sum_{j=1}^{M} Q_j}$$

Accordingly, by performing processing for determining the existence probability β_j of the projection point T_j for every projection point T_j
5   overlapping when viewed from the reference viewpoint R for every direction, the three-dimensional shape of the object can be obtained. When generating the image of the object viewed from the virtual viewpoint P, the virtual viewpoint P is set on a
10 space in which the projection planes L_j are set so as to determine the color information of each point of the image to be generated as shown in Fig.49, for example. In this method, the color information K_A of a point A on the image to be generated is
15 determined by using the following equation 69, for example, from color information K_j and existence probability β_j of projection points T_j overlapping with the point A when viewed from the virtual viewpoint P.
20 [Equation 69]

$$K_A = \sum_{j=1}^{M} \beta_j K_j$$

By determining the color information for every point on the image to be generated, the image (virtual viewpoint image) of the object viewed from the
25 virtual viewpoint P is obtained. When only a focusing degree Q_n of a projection point T_n has a distinctive large value on the generated virtual viewpoint image as shown in Fig.47A, only an existence probability β_n of the projection point T_n
30 becomes large. Therefore, when performing mixing

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processing on the color information using the
equation 69, contribution ratio of the color
information K_n of the projection point T_n to the
color information K_A of the point A on the generated
5   image becomes high so that it is rendered clearly.
In addition, as shown in Fig.47B, when it is
difficult to estimate the distance of the surface of
the object, since the contribution ratio to the
color information K_A of the point A on the generated
10   image becomes low so that it is rendered vaguely.
As a result, the discontinuous large noise that
appears when erroneous estimation of distance is
performed can be decreased, so that an image that
looks good for the observer can be generated.
15   In addition, the image generation method
of the present invention can be implemented simply
by using texture mapping that is a basic method in
computer graphics. Therefore, computing workload
can be decreased such that processing can be
20   properly performed by three-dimensional graphics
hardware mounted on a general personal computer.
            However, in the image generation method of
this invention, the focusing degree Q_j is calculated
for each of the projection points T_j overlapping
25   viewed from a viewpoint such as the reference
viewpoint, and the existence probability β_j is
determined. Therefore, there is a case where the
projection points overlapping viewed from the
virtual viewpoint P include more than one point at
30   which the existence probability is very high
depending on the position relationship of the
reference viewpoint and the virtual viewpoint. In
such a case, if the color information of each
projection point are mixed in a ratio according to
35   the existence probability, there is a case where
color information of a point on the image to be
generated may exceed a limit of an effective color

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information.

       Thus, in the same way as described in embodiments described so far, a case is considered in which two projection planes L_1 and L_2, a

5   reference viewpoint R and a virtual viewpoint R are set in a space where the object exists as shown in Fig.50. In this example, assuming that color information of the projection points T_1, T_2, T'_1 and T'_2 are K_1, K_2, K'_1 and K'_2, and existence

10   probabilities of the object are β_1, β_2, β'_1 and β'_2 respectively.

       When the existence probabilities of the object β_1, β_2, β'_1 and β'_2 are determined on a line passing through the reference viewpoint R, the

15   surface of the object Obj exists near the projection points T'_1 and T_2 in the example shown in Fig.50. Therefore, the existence probability of each of the projection points T'_1 and T_2 becomes higher than projection points T_1 and T'_2. In this case, the

20   existence probabilities β_1, β_2, β'_1 and β'_2 of the projection points T_1, T_2, T'_1 and T'_2 are represented by the following equation 70 and equation 71.

   [Equation 70]

$$\beta_1 \cong 0, \quad \beta_2 \cong 1$$

25   [Equation 71]

$$\beta'_1 \cong 1, \quad \beta'_2 \cong 0$$

       The color information K_A at the point A of the image plane of the virtual viewpoint P is obtained by adding, after assigning weights

30   according to the existence probabilities β'_1 and β_2, color information K'_1 and K_2 of the projection points T'_1 and T_2 overlapping with the point A on the image plane when viewed from the virtual viewpoint P according to the equation 69, and the color

35   information K_A is represented as shown in the

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following equation 72.

[Equation 72]

$$K_A = \beta_1' K_1' + \beta_2 K_2$$

In addition, the equation can be approximated to the
5   following equation 73 according to the equation 70
and the equation 71.

[Equation 73]

$$K_A \fallingdotseq K_1' + K_2$$

     However, when the object Obj is viewed from
10   the virtual viewpoint P, since the projection point
T'$_1$ is blocked by the projection point T$_2$, actual
color information at the point A on the image
surface should be K$_A$=K$_2$. That is, brightness of
each component (R,G,B) of the generated color
15   information K$_A$ at the point A on the image is
increased by K'$_1$ compared with the actual color
information.

     In addition, when each component of the
color information K'$_1$ and K$_2$ of the projection points
20   T'$_1$ and T$_2$ has large brightness, the color
information K$_A$ of the point A exceeds a limit of an
effective color space. Therefore, clipping
processing is necessary for the color information to
fall within the limit of the effective color space.
25   Thus, in the image generation method of
this invention, transparency that may take plural
gradations from transparent to opaque is provided to
each projection point based on the existence
probability of the projection point. In this case,
30   the mixing processing is performed successively from
a projection point of the generated image far from
the viewpoint to a projection point near the
viewpoint, in which color information obtained by
mixing processing up to a projection point is
35   obtained by performing interior division between

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color information at the projection point and color
information obtained by mixing processing up to a
previous projection point with a ratio according to
the transparency. The color information obtained by
5   the mixing processing is interior division between
color information at a stage and color information
at the next stage.

For explaining the principle of the mixing
processing of the color information, assuming a case
10   in which projection planes $L_j(j=1,2,…,M)$, projection
points T_j, and a vector K_j having components of red
(R), green (G) and blue (B) and representing color
information of the projection point are set in a
color space V as shown in Fig.51A, for example. It
15   is assumed that the color information V is
represented by the following equation 74.
[Equation 74]

$$K_j \in V, V \equiv \left\{(R,G,B) \mid 0 \le R \le 1, 0 \le G \le 1, 0 \le B \le 1\right\}$$

In addition, it is assumed that the transparency α_j
20   of the projection point T_j is set such that it
satisfies a condition shown in the equation 75.
[Equation 75]

$$0 \le \alpha_j \le 1$$

At this time, the color information D_m obtained by
25   mixing processing up to the argument j=m is
represented by recurrence formulas shown in
equations 76 and 77. Then, color information D_M of
the projection plane L_M nearest to the virtual
viewpoint P, that is, color information D_M obtained
30   by performing mixing processing up to the argument
j=M becomes the color information K_A at the point A
on the image plane of the image to be generated.
[Equation 76]

$$D_m = \alpha_m K_m + \left(1 - \alpha_m\right)D_{m-1}$$

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[Equation 77]

$$D_1 = \alpha_1 K_1$$

In addition, in this case, as shown by the relationship of the equations 75 and 76, the color

5　information D_m is an internally divided point between the vector K_m and the color information D_{m-1} in the color space V. Therefore, as to the color information D_m, when $K_m \in V$ and $D_{m-1} \in V$ are satisfied, $D_m \in V$ holds true as shown in Fig.51B.

10　　　　　Then, when the conditions of the equations 74 and 75 are satisfied, it is ensured that the following equation 78 holds true with respect to the color information D_M at the virtual viewpoint P.

[Equation 78]

15　　　$$D_M \in V$$

That is, by setting the color information K_j and the transparency α_j at the projection point T_j so as to satisfy the equations 74 and 75, the color information D_M of the point A of the image to be

20　generated can always fall within a proper color space V.

　　　　　As mentioned above, for generating images obtained by viewing the same object from plural virtual viewpoints, by performing the mixing

25　processing of the color information using the transparency α_j, all images can be generated within a limit of proper color information even when calculating the color information and the transparency of the projection point from a

30　viewpoint (reference viewpoint) if the color information and the transparency satisfies the equations 74 and 75.

　　　　　Thus, transparencies α_1, α_2, α'_1 and α'_2 than can be provided by the following equations 79

35　and 80 are provided to the projection points T_1, T_2,

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T'$_1$ and T'$_2$ respectively, for example, in the example
shown in Fig.50.

[Equation 79]

$$\alpha_2 = \beta_2, \quad \alpha_1 = 1$$

5   [Equation 80]

$$\alpha'_2 = \beta'_2, \quad \alpha'_1 = 1$$

For obtaining color information of each point of the
virtual viewpoint, mixing processing is performed
successively from a projection point far from the

10   virtual viewpoint toward a projection point near the
projection point, and color information obtained by
mixing processing up to a projection point is
obtained by performing interior division between
color information at the projection point and color

15   information obtained by mixing processing up to a
previous projection point at a ratio of
transparencies, so that color information K$_A$ of the
point A of the image viewed from the virtual
viewpoint P is represented by the following equation

20   81.

[Equation 81]

$$K_A = \alpha_2 K_2 + \left(1 - \alpha_2\right) \alpha'_1 K'_1$$

The equation 81 can be represented as the following
equation 82 according to the equation 70, the

25   equation 71, the equation 79 and the equation 80.
The equation 82 represents good approximation of
actual color information.

[Equation 82]

$$K_A \fallingdotseq K_2$$

30   As mentioned above, when performing image generation
using the existence probability information as it is,
there is no problem if the reference viewpoint P
and the viewpoint P of the image to be generated are

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the same.　But, when they are different, brightness
may increase near blocked region.　On the other hand,
according to image generation in which the existence
probability information is changed to transparency,
5　the above mentioned phenomenon can be prevented.

In addition, when the reference viewpoint
R and the virtual viewpoint P are different in the
image generation using the existence probability
information as it is, there is no guarantee that
10　color information that is calculated using after-
mentioned equations falls within an effective color
information limit, and correction processing is
necessary, for example.　On the other hand,
according to the image generation in which the
15　existence probability information is converted to
the transparency, such correction is not necessary.

In addition, according to the image
generation in which the existence probability
information β is converted to transparency α, a
20　semitransparent object can be efficiently
represented, so that there is an effect that the
present invention can be applied more widely to more
objects in the actual world.

Next, an example of a mathematical model
25　used in processing in generating the image using the
image generation method of the present invention is
describe.

Figs.52 and 53 are schematic diagrams for
explaining the mathematical model of the image
30　generation method of the present invention.　Fig.52
is a diagram, showing relationship among projection
points, corresponding points and points on the image
to be generated.　Fig.53 is a diagram for explaining
a method for converting points on the space to
35　pixels on the image.

For generating the image viewed from the
virtual viewpoint P using the image generation

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method of this invention, color information or brightness information of a point on the image viewed from the virtual viewpoint using perspective projection conversion, for example. In this example,

5   a case is considered where the viewpoint C of the camera, the projection planes L_j (j=1,2,…,M) and the virtual viewpoint P are set as shown in Fig.52, for example.

Generally, a matrix for projecting a

10   projection point $T_m(X,Y,Z)$ on the three-dimensional space to a point (x,y) of an image viewed from the virtual viewpoint P, that is, an image to be generated is provided as a 3 rows and 4 columns matrix. The projection matrix, and the matrix Φ_0

15   representing the perspective projection conversion of focal length f in which the original point is the center are the same as those described in the first embodiment and the like.

In addition, also relationship between the

20   image coordinates (x,y) and the digital image coordinates (u,v) shown in Fig.53 is the same as that described in the first embodiment. Although the digital image coordinates (u, v) take discrete values when writing into or reading out the two-

25   dimensional array, it is assumed that the coordinates take continuous values unless otherwise specified, and that proper discretization processing is performed when accessing the array. In addition to the coordinate conversion, conversion for

30   correcting distortion by aberration of the lens can be performed.

(Embodiment 3-1)

Figs.54-57 are schematic diagrams for explaining the image generation method of the

35   embodiment 3-1 of this invention. Fig.54 is a flow diagram showing a generation procedure for the image. Fig.55 is a diagram for explaining a method for

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setting the projection point series. Fig.56 is a flow diagram showing a concrete example of processing of the step 10305 of Fig.54. Fig.57 is a diagram for explaining a rendering method.

5   The image generation method of this embodiment 3-1 is a method for generating an image using the principle described before. As shown in Fig.54, the method includes a step 101 of obtaining plural images having different focusing distances, a

10   step 102 of setting a viewpoint (virtual viewpoint) of the observer, a step 103 of obtaining the three-dimensional shape of the object based on the obtained images, and a step 104 of rendering an image of the three-dimensional shape of the object,

15   obtained in the step 103, when viewed from the virtual viewpoint.
       The step 103 includes a step 10301 of setting projection planes of multi-layered structure, a step 10302 of determining the reference viewpoint

20   for obtaining the three-dimensional shape of the object, a step 10303 for setting projection point series, corresponding points and the like, a step 10304 of keeping the texture array, that is, an area for storing the color information and the existence

25   probability of the projection points, and a step 10305 of determining the color information and the existence probability of the projection point.
       In the image generation method of this embodiment 3-1, the plural images are obtained by

30   taking the object by changing the focusing distances as shown in Fig.54, for example (step 101). Although the image to be obtained may be a color image or a black and white image, it is assumed that the color image in which each point (pixel) is

35   represented by color information using three primary colors of red (R), green (G) and blue (B) is obtained in this embodiment 3-1 in the following

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descriptions.

Next, a position (virtual viewpoint) at which the observer observes the object is set (step 102). Next, the three-dimensional shape of the
5   object is obtained using the obtained images of the object (step 103). Then, after obtaining the three-dimensional shape of the object, the image of the object viewed from the virtual viewpoint is generated (step 104).
10   In the step 103, first, the projection planes L_j ($j \in J$, $J \equiv \{1, 2, \ldots, M\}$) of the multi-layered structure are set (step 10301) as shown in Fig.54, for example. As the projection planes L_j, projection planes having plane shape are placed in
15   parallel as shown in Fig.43, for example. It is desirable that the placement intervals of the projection planes are the same as focusing distances of the images obtained in the step 101 as shown in Fig.44, for example, but they may not necessarily be
20   the same as the focusing distances.

Next, a viewpoint for obtaining the three-dimensional shape of the object is determined, in other words, a point (reference viewpoint) R that is a reference when obtaining the probability that the
25   surface of the object exists on the projection point is determined (step 10302). The reference viewpoint R may be the same as the virtual viewpoint P or may not be the same. When generating images of the object viewed from plural virtual viewpoints P
30   successively, the reference viewpoint may be determined as a barycenter of the virtual viewpoints.

Next, projection point series that are groups each including projection points on a line that pass through the reference viewpoint R, and
35   points (corresponding points) corresponding to the projection points are set (step 10303). The projection point series are defines as sets of cross

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points (projection points) T_j between the lines that pass through the reference viewpoint R and the projection planes L_j. The projection point series S can be described as $S=\{T_j|j\in J\}$, and if the set is σ,

5　$S\in\sigma$ holds true.

　　　　Next, an array (texture array) for holding the image to be texture-mapped to each projection point is kept on a memory in an apparatus for generating the image, for example (step 10304). At

10　this time, the array to be kept includes color information and existence probability information by 8 bits for each pixel as texture information corresponding to the position of the projection point.

15　　　　In the step 10304, correspondence between the two-dimensional digital coordinates (U_j,V_j) of the pixel of the texture array and the three-dimensional coordinates (X_j,Y_j,Z_j) of the projection point T_j is also set. At this time, for example,

20　values of (X_j,Y_j,Z_j) for every (U_j,V_j) may be set as a table. Or, only some values of (X_j,Y_j,Z_j) of representative (U_j,V_j) may be set and other correspondences are obtained by interpolation processing such as linear interpolation, for example.

25　　　　Next, color information K_j and existence probability β_j for pixels corresponding to each projection point T_j kept in the step 10304 are determined based on the images of the object obtained in the step 101 (step 10305). At that time,

30　as to the color information and the existence probability, the projection points T_j on the projection point series S are scanned successively within a limit of $T_j\in S$, and the processing is repeated within a limit of the projection point

35　series $S(\in\sigma)$, so that double loop processing is performed.

　　　　In the processing of the step 10305, first,

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as shown in Fig.56, the projection point series S to be scanned is initialized to a start position (step 10305a). Then, next, the projection point T_j for scan is initialized to a start position within the

5　projection point series S, for example, initialized to j=1 (step 10305b).

Next, color information K_j of coordinates (X_j^*, Y_j^*, Z_j^*) of the projection point T_j is determined (step 10305c). In the step 10305c, first, a

10　position, in the image plane (image sensor), that corresponds to a point at coordinates (X_j^*, Y_j^*, Z_j^*) when the point is taken is calculated. Then, the color information of a pixel (U_j^*, V_j^*), on the texture array, corresponding to the projection point

15　T_j is determined to be color information at (u_{ij}^*, v_{ij}^*) $(i \in I)$, for example.

Next, the focusing degree Q_j of the projection point T_j is determined. The focusing degree Q_j is calculated using the equation 65 based

20　on the local spatial frequency of the corresponding point, for example (step 10305d).

Next, after processing up to the step 10305d has been performed, the projection point T_j is updated, and it is determined whether every

25　projection point $T_j \in S$ has been scanned (step 10305e). When every point has been scanned, the step goes to the next step 10305f. If every point has not been scanned, the step returns to the step 10305c.

30　When it is determined that every point has been scanned in step 10305e, next, the probability (existence probability) β_j that the object exists on the projection point is determined for every projection point T_j $(j \in J)$ on the

35　projection pint series S based on the focusing degree Q_j of each projection point T_j calculated in the step 10305d (step 10305f). The existence

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probability β_j is determined using the equation 68,
for example. Since it is only necessary for the
existence probability β_j to satisfy the equation 66
and the equation 67 basically, equations other than
5   the equation 68 can be used.

Next, the projection point series S is
updated and it is determined whether every
projection point series $S\in\sigma$ has been scanned (step
10305g). If every projection point series has been
10   scanned, the processing of the step 103, that is,
processing for obtaining the three-dimensional shape
of the object completes. If every projection point
series has not been scanned, the step returns to the
step 10305b.

15   In the step 10305g, when it is determined
that every projection point series has been scanned,
next, an image of the object, represented by using
the projection planes L_j (j=1,2,…,M), viewed from the
virtual viewpoint P is generated by rendering
20   according to the existence probability β_j (step 104).
It is assumed that the coordinates of the image
plane of the virtual viewpoint P are represented by
u_p and v_p as shown in Fig.57.   In this case, the
color information K_p^* of a pixel $p^*(u_p^*,v_p^*)$ on the
25   image plane is determined by multiplying color
information $\{K_j^*\mid j\in J\}$ of projection point series
$\{T_j^*\mid j\in J\}$ on a line connecting between the virtual
viewpoint P and the pixel p^* by corresponding
existence probability $\{\beta_j^*\mid j\in J\}$, and by adding the
30   multiplied color information, so that the color
information K_p^* is represented by the following
equation 83.

[Equation 83]

$$K_P^* = \sum_{j=1}^{M} \beta_j^* K_j^*$$

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Then, by determining the color information for every
pixel on the image plane by using the equation 83,
the image of the virtual viewpoint P can be obtained.

By calculating K_p^* using the following
5   equation 84 instead of the equation 83, it can be
ensured that K_p^* always falls within a limit of an
effective color space even when positions of the
reference viewpoint R and the virtual viewpoint P
are different.

10   [Equation 84]

$$K_P^* = \frac{\sum_{j=1}^{M} \beta_j^* K_j^*}{\sum_{j=1}^{M} \beta_j^*}$$

Although color information is determined by scanning
pixels on the image plane in this procedure, the
procedure is not limited to this. For example,
15   rendering processing can be performed by a general
graphic library such as OpenGL, DirectX and the like
by passing, to the library, data such as the
configuration of the projection planes L_j, the
texture array, setting of the virtual viewpoint P
20   and the like.

Accordingly, the generation processing of
the virtual viewpoint image of this embodiment 3-1
completes, so that the generated image is output to
the image display means such as a CRT (Cathode Ray
25   Tube), a liquid crystal display and the like. As to
the image displayed on the image display means, in
images of the object, color information of a
projection point having low focusing degree Q
calculated in the step 10305d has small contribution
30   to color information of a point on the generated
image. Therefore, the projection point at which
reliability of distance estimation is low is

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rendered vaguely. As a result, for example, the image does not appear to lack partial image or to have extremely deteriorated image quality as the image generated by the conventional method, but the

5　deterioration is not annoying for the user.

Figs.58-61 are schematic diagrams showing a general configuration of the apparatus for generating the image using the image generation method of this embodiment 3-1. Fig.58 is a block

10　diagram showing the configuration of the apparatus. Figs.59-61 are diagrams showing a configuration example of the object image taking means.

In Fig.58, 2 indicates the image generation apparatus, 201 indicates a multiple focus

15　image (object image) obtaining means, 202 indicates a virtual viewpoint setting means, 203 indicates a projection plane etc. setting means, 204 indicates a texture array keeping means, 205 indicates a color information/existence probability determination

20　means, 206 indicates a rendering means, 207 indicates a generated image output means, 3 indicates a multiple focus image (object image) taking means, 4 indicates a viewpoint information input means, 5 indicates an image display means. In

25　Fig.59, 6 indicates a polarizing binary optical system, 7, 7A and 7B indicates image sensors, 8 indicates a beam splitter, ObjA and ObjB indicate objects. In Fig.60, 9 indicates a polarizing filter. In Fig.61, 10 indicates a variable focus lens, 11a,

30　11b, 11c and 11d indicate fixed focus lenses, 12 indicates a lens holder.

As shown in Fig.58, for example, the image generation apparatus 2 used for generating the image using the image generation method of this embodiment

35　includes the multiple focus image (object image) obtaining means 201 for obtaining plural images of different focusing distance, the virtual viewpoint

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setting means 202 for setting the viewpoint (virtual viewpoint) of the image to be generated, the projection plane etc. setting means 203 for setting projection planes of the multi-layered structure on the virtual three-dimensional space, the texture array keeping means 204 for assigning, to a memory, the array of the image (texture image) to be mapped to the projection plane, the color information/existence probability determination means 205 for determining the color information and the existence probability on the point (to be referred to as projection point hereinafter) on each projection plane, the rendering means 206 for determining color information of each pixel on the image to be generated, and the generated image output means for outputting the image generated by the rendering means 206.

The object image obtaining means 201 obtains the image of the object taken by the object image taking means 3 including a lens, that changes focusing distance according to polarization component, such as the polarizing binary optical system (refer to document 12: Japanese Laid-Open Patent Application No. 2000-258738, for example). In addition, it is not limited to the polarizing binary optical system, and the image taken by an image taking means including a variable focus lens (refer to document 13: Japanese Patent No. 3303275, for example) can be obtained. In addition to that, by holding lenses, having different focal length, as one, images taken by changing lenses at high speed can be obtained. In this case, the object image obtaining means 201 can successively obtain the position and posture of the object that changes every moment at constant intervals of 30 Hz, for example, or can obtain a still image of the object at a desired time. In addition, an image recorded

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in a recording medium that is electrical, optical or
magnetic after being taken by the object image
taking means 3 can be obtained. It is desirable
that the images of the object are taken at the same
5   time. However, this is not always so when change of
the position and the posture of the object is slow
enough so that the object is regarded as a still
object.

       The virtual viewpoint setting means 202
10   sets position, direction, image angle and the like,
for example, as parameters of the viewpoint (virtual
viewpoint) of the image to be generated. The
virtual viewpoint may be automatically determined by
the virtual viewpoint setting means 202, or may be
15   determined based on information input, by the user,
using the viewpoint information input means 4 such
as the mouse or the key board and the like. The
viewpoint information input means 4 may be a
position/posture detection sensor mounted by the
20   user. In addition, the viewpoint information input
means 4 may be one provided by other program or one
provided via the network.

       The projection plane etc. setting means
203 performs processing of the steps 10301, 10302
25   and 10303 shown in Fig.54, for example.

       The texture array keeping means 204
performs the processing of the step 10304 shown in
Fig.54, and holds information on the color
information and the existence probability for each
30   pixel, for example. The texture array keeping means
204 holds a texture array representing each of
three-primary color of red (R), green (G) and blue
(B) and the existence probability using 8 bits.
However, the present invention does not depend on
35   such particular data representation format.

       The color information/existence
probability determination means 205 performs

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processing of the step 10305 shown in Fig.24, and performs processing from the step 10305a to the step 10305g shown in Fig.56, for example. The rendering means 206 performs processing of the step 104 shown

5 in Fig.54 based on the result of the color information/existence probability determination means 205 so as to generate the image of the object viewed from the virtual viewpoint P.

The virtual viewpoint image generated by

10 the rendering means 206 is output from the generated image output means 207, and is displayed by the image display means 5 such as a CRT, a LCD (Liquid Crystal Display) and a PDP(Plasma Display Panel) and the like. The image display means 5 may be a

15 display means like a two-dimensional plane, or may be a display means having a curved surface surrounding the user. By using a display apparatus that can display stereoscopically as the image display means 5, images that are independent for

20 right and left eyes of the user can be presented after determining two viewpoints corresponding to the right and left eyes of the user by the virtual viewpoint setting means 202 and generating a stereoscopic image from the two viewpoints. In

25 addition, by using a three-dimensional display that can generate imagse from more than two virtual viewpoints and can display images having more than two parallaxes, a stereoscopic image can be presented to equal to or more than one user.

30 The generated image output means 207 may be a means that outputs the generated image not only to the image display means 5 but also to a recording medium that is electrical, magnetic or optical, for example.

35 In addition, although not shown in the figure, the image generation apparatus 2 can be provided with a storing means for storing the

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generated image to store the generated image, and
the stored image can be output according to an
instruction of the user so as to display the image
on the image display means 5.

5   In addition, by using a camera in which
the paralyzing binary optical system is embedded as
the taking means 3, the object Obj can be taken
using two kinds of focusing distances. The
paralyzing binary optical system is an optical
10   system using material presenting optical anisotropy
(birefringence). As shown in Fig.59A, for example,
focusing distances f_1 and f_2 are different between a
case where the polarizing component of light passing
through the paralyzing binary optical system 6 is p
15   component and a case where the polarizing component
is s component. When the image is formed on one
image sensor 7 like a general taking means, as to
the image obtained from one image sensor 7, an image
of p component and an image of s component are
20   overlapped, that is, an image taken with focusing
distance f_1 and an image taken with focusing
distance f_2 are overlapped. Therefore, as shown in
Fig.59B, for example, the light passed through the
polarizing binary optical system 6 is separated by a
25   beam splitter 8 so that the light of the p component
is focused on a first image sensor 7A and the light
of the s component is focused on a second image
sensor 7B. As a result, the image of focusing
distance f_1 and the image of focusing distance f_2 can
30   be separated and each of them can be obtained.
            For example, as shown in Fig.59B, when the
object ObjA exists near the focusing distance f_1 and
the object ObjB exists near the focusing distance f_2,
the object ObjA becomes sharp and the object ObjB
35   becomes blurred in the image of the first image
sensor 7A, that is, in the image formed by the light
of the p component as shown in Fig.59C. In contrast,

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the object ObjA becomes blurred and the object ObjB becomes sharp in the image of the second image sensor 7B.

In addition, for dividing the image taken
5 by using the polarizing binary optical system 6, a polarizing filter 9 may be provided between the polarizing binary optical system 6 and the image sensor 7 as shown in Fig.60A, for example, instead of using the beam splitter 8. In this case, the
10 placed polarizing filter 9 is configured such that a filter 9A for the p component and a filter 9B for the s component are arranged like a checked lattice as shown in Fig.60B, for example. In this case, when the size of each of the filters 9A and 9B is
15 the same as the size of the pixels of the image sensor 7, or is n×n pixels, two images shown in Fig.59C can be obtained by subtracting pixels corresponding to p component or s component from the image obtained by the image sensor 7.
20 In addition, for taking the plural images having different focusing distances, a variable focus lens 10 may be used as shown in Fig.61A, for example, instead of using the polarizing binary optical system 6. By using the variable focus lens
25 10, images of four focus points f_1, f_2, f_3 and f_4 can be obtained using one lens as shown in Fig.61A, for example.

In addition, instead of changing a refractive index of a medium of a lens to change the
30 focus position like the variable focus lens 10 and instead of using the polarizing binary optical system 6, the images can be taken by holding fixed focus lenses 11a, 11b, 11c and 11d, as one with a lens holder 12, each having a fixed focusing
35 distance that is different each other and by rotating the lens holder 12 to switch each lens at high speed as shown in Fig.61B.

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As described above, according to the image generation method of this embodiment 3-1, the method of the present invention does not intend to obtain a geometrical object model accurate for every case and every portions like the conventional method. But, assuming that an estimated value having adequate reliability cannot be obtained in the distance estimation depending on picture-taking conditions and portions, a portion, by which an estimated value of low reliability is obtained, is drawn vaguely so as to provide the portion with low contribution to image generation for avoiding extreme image deterioration, and a portion, by which distance data of high reliability is obtained, is drawn clearly so as to provide the portion with high contribution to image generation. Therefore, deterioration of image of the portion having low estimation reliability can be inconspicuous so that the virtual viewpoint image having small deterioration can be obtained in the eyes of the user.

In addition, according to the image generation method of this embodiment 3-1, since the virtual viewpoint image can be generated using texture mapping, workload of the apparatus in the image generation processing can be decreased and the virtual viewpoint image can be generated at high speed.

In addition, the virtual viewpoint image generation apparatus 2 does not need to be a specific apparatus. For example, the virtual viewpoint image generation apparatus 2 can be realized by a computer a program, for example. In such a case, by generating a program that can cause the computer to execute each step shown in Figs.54 and 55 and by executing the program on the computer, the virtual viewpoint image having small image deterioration can be easily generated at high speed

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even though the computer is a general personal
computer.   In addition, the program can be provided
by recording it into a recording medium that is
magnetic, electrical or optical, and also can be
5   provided via a network.
            The configuration of the image generation
apparatus, the method for generating the image and
processing procedures described in this embodiment
3-1 are merely examples, and the principal object of
10   the present invention is to provide the existence
probability to the image to be mapped to the
projection planes configured by multi-layers and to
render a part, at which the reliability of distance
estimation is low, vaguely by texture-mapping the
15   part to plural projection planes.   Thus, within a
limit that does not largely differ from the scope,
the present invention is not dependent on a
particular processing method or implementation.
            In addition, in the image generation
20   method of this embodiment 3-1, although a case is
described as an example in which a color image in
which the point (pixel) is represented by color
information using three primary color of red (R),
green (G) and blue (B) is obtained and the three-
25   dimensional shape of the object is generated, the
image to be obtained is not limited to the color
image.   In the image generation method of this
embodiment 3-1, a black and white image in which the
point (pixel) is represented by brightness (Y) and
30   color-difference (U, V) may be obtained so as to
generate the virtual viewpoint image.   In the case
when the image to be obtained is the black and white
image, the virtual viewpoint image can be obtained
by the procedure described in this embodiment 3-1
35   using the brightness information (Y) as information
corresponding to the color information.
            Figs. 62 and 63 are schematic diagrams

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showing a general configuration of the image
generation system using the image generation
apparatus of this embodiment 3-1. Fig.62 is a
diagram showing a configuration example of the image
5   generation system, and Fiog.63 is a diagram showing
another configuration example of the image
generation system.

The image generation apparatus 1 of this
embodiment 3-1 can be applied to the image
10   generation system shown in Fig.62, for example. In
this case, when the user User specifies desired
viewpoint position, direction and image angle using
the viewpoint information input means 4 such as a
mouse, the image generation apparatus 2 obtains the
15   images of the object Obj taken by the taking means 3.
The image generation apparatus 1 that obtains the
images of the object Obj generates the image of the
object Obj viewed from the viewpoint position,
direction and image angle specified by the user User
20   according to the procedure described in this
embodiment 3-1. Then, the generated image is
displayed on the image display means 5 so that the
image is presented to the user User.

The taking means 3 may be placed at a
25   place geographically near the place where the user
User exists, or may be placed in a place
geographically apart.

In addition, the image generation
apparatus 1 of this embodiment 3-1 can be applied
30   not only to the unidirectional image generation
system in which relationship between the user User
and the object Obj is fixed, as shown in Fig.62, for
example, but also to a bi-directional communication
system such as TV phone o TV conference.

35   When applying the image generation
apparatus 2 of this embodiment 3-1 to the bi-
directional communication system, it is only

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necessary to provide a taking means 3A for taking
the user UserA and a taking means 3B for taking the
user UserB as shown in Fig.63, for example.
Accordingly, the user UserA can generate the image
5　of the user UserB viewed from a desired viewpoint
using the image of the user UserB taken by the
taking means 3B so as to display the image on the
image display means 4A.　In the same way, the user
UserB can generate the image of the user UserA
10　viewed from a desired viewpoint using the image of
the user UserA taken by the taking means 3A so as to
display the image on the image display means 4B.　In
this example, the image generation apparatus 2 may
be placd at each of the users UserA and UserB, or
15　may be placed at either one of the users UserA and
UserB.　In addition, by placing the image generation
apparatus 2C on the network 13 such as the Internet
or the company LAN and the like, the image viewed
from the virtual viewpoint can be generated and
20　displayed without placing the image generation
apparatus 2 at any of the users UserA and UserB.
　　　　Although communications between two users
are shown in Fig.63, among more users, similar image
generation can be performed.　In the case, assuming
25　a virtual space used for communication separately
from the actual space in which users actually exist,
by providing an image of other user according to
position relationship with each other, the system
can provide users with feeling as if to share
30　virtual space (cyber space) on the network.
　　　　The configuration of the system shown in
Figs.62 and 63 shows one application example of the
image generation apparatus in this invention, and
the present invention is not necessarily limited to
35　such configuration.　That is, placement, form,
implementation and the like of each apparatus and
means can be set as one chooses as long as without

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exceeding the scope of the present invention.
(Embodiment 3-2)
Fig.64 is a flow diagram showing
characteristic feature of the embodiment 3-2.   In
5   the embodiment 3-2, in the processing for generating
the virtual viewpoint image described in the
embodiment 3-1, image generation is performed by
converting the existence probability to transparency
instead of using the existence probability of the
10   projection point determined in the step 10305f.
In this case, as to the configuration of
the image generation apparatus 1 and the whole
processing procedure, forms similar to those
described in the embodiment 3-1 can be adopted.
15   Therefore, only different points are described in
the following.
In the embodiment 3-1, color information
of each point on the image viewed from the virtual
viewpoint P is determined using the equation 69 by
20   using the existence probability β_j determined in the
step 10305f so as to generate the virtual viewpoint
image.   In that case, as described with Fig.50, the
obtained color information may be largely different
from actual color information of the object surface
25   according to the shape of the object or the position
relationship between the reference viewpoint and the
virtual viewpoint.   Thus, in this embodiment 3-2, as
a method for solving the problem, a method is
described in which the existence probability is
30   converted to transparency so as to mix color
information of each projection point in a ratio
according to the transparency.   In this case, the
step of converting the existence probability into
the transparency can be performed after the step
35   10305f in the step 103, or can be performed between
the steps 103 and 104.   In this embodiment, as shown
in Fig.64, the step 105 of determining the

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transparency by converting the existence probability
is added just after the step 10305f of determining
the existence probability.

In this case, although the texture array
5   is kept for keeping the color information and the
existence probability in the step 10304 of keeping
the texture array in the embodiment 3-1, a texture
array for holding the color information and the
transparency is kept in the step 10304 in this
.10 embodiment 3-2.

The transparency α_j is calculated based on
the existence probability β_j. Then, like the step
10305f in the embodiment 3-1, the existence
probability is calculated once in the step 10305f,
15 and the transparency α_j is calculated in the next
step 105 in this embodiment 3-2.

In addition, in step 104 for performing
rendering processing in this embodiment 3-2, D_j is
successively calculated according to the equations
20 11-13 instead of the equation 83 or 84 described in
the embodiment 3-1. Therefore, color information
K_j^* of a pixel $p^*(u_p^*, v_p^*)$ on the image plane is
calculated by the following equation 85.

[Equation 85]

$$K_P^* = D_M$$
$$= \alpha_M K_M + (1 - \alpha_M)\alpha_{M-1} K_{M-1} + \cdots$$
$$+ (1 - \alpha_M)(1 - \alpha_{M-1}) \cdots (1 - \alpha_2)\alpha_1 K_1$$

25

The image generation method in this embodiment 3-2
is as mentioned above. The method for calculating
the transparency α_j based on the existence
probability β_j is the same as the method described
30 with reference to Fig.19B in the first embodiment.

According to this embodiment 3-2, like the
embodiment 3-1, the virtual viewpoint image in which

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the partial image deterioration is inconspicuous can be generated easily at high speed.

In addition, as described in the embodiment 3-1, in image generation using the existence probability information as it is, there may be a case in which brightness increases near the blocking area of the object when the reference viewpoint and the virtual viewpoint are different. On the other hand, as described in the embodiment 3-2, in the image generation for converting the existence probability information to transparency, there is an effect to prevent the phenomenon. Therefore, a virtual viewpoint image having small image deterioration and more similar to the actual object can be obtained.

In addition, as described in the embodiment 3-1, in the image generation using the existence probability information as it is, there is no guarantee that mixed color information falls within an effective color information limit when the reference viewpoint and the virtual viewpoint are different, so that correction processing is required, for example. On the other hand, according to the image generation for converting the existence probability information to transparency like the embodiment 3-2, such correction is not necessary. Therefore, the image generation processing can be simplified.

In addition, in image generation for converting the existence probability information to the transparency like the virtual viewpoint image generation method of this embodiment 3-2, a semitransparent object can be efficiently represented, so that there is an effect that the present invention can be applied to more objects in the actual world.

The virtual viewpoint image generation

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method described in this embodiment 3-2 is an
example, and the principal object of the present
embodiment is to generate the virtual viewpoint
image by converting the existence probability
5   information to the transparency. Therefore, the
present invention is not dependent on particular
calculation method or processing procedure within a
limit largely exceeds the object.

Also in the image generation method of
10   this embodiment 3-2, the image to be obtained may be
a color image or black and white image. When the
black and white image is obtained, the mixing
processing described in this embodiment 3-2 is
performed using brightness information (Y) as
15   information corresponding to the color information.

Fig.65 is a schematic diagram for
explaining other generation method in the image
generation method in this invention.

In the image generation method in the
20   embodiment 3-1 and the embodiment 3-2, it is assumed
that a general lens is used for obtaining the plural
images having different focusing distances, and
approximation based on a pinhole optical system is
performed for projection of the color information.
25   However, when the images having different focusing
distances are used like the image generation method
of this invention, a parallel projecting system can
be set as shown in Fig.65 for performing projection
of the color information by obtaining the plural
30   images using a telecentric lens. In this case,
assuming that a cross point of a line, passing
through the point A on the image to be generated,
perpendicular to the image surface and the
projection plane L_j is the corresponding point T_j,
35   the probability β_j that the object exists on the
projection point T_j is obtained by the procedure
described in the embodiment. In this case, as shown

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in Fig.65, the x component and the y component of
the corresponding point G_1 to be texture-mapped to
the projection point T_1 become the x component and
the y component of the point G on the image sensor.

5   On a generated image Img_i, a part the same as the
part appearing on the corresponding point G_1 is on a
line, passing through the point G on the image
sensor, perpendicular to the image sensor. Thus,
regarding these points as corresponding points G_i,

10 the color information K_1 and the focusing degree Q_1
of the projection point T_1 are determined. Then,
after performing this processing for each projection
point T_j on the same line, the existence probability
β_j can be obtained from the focusing degree of each

15 projection point.
    (Effects of the third embodiment)
       As mentioned above, the image generation
method of the third embodiment provides color
information or brightness information and the

20 probability (existence probability) that the surface
of the object exists to plural projection points
that overlap when viewed from the reference
viewpoint for obtaining the three-dimensional shape
of the object. That is, the method of this

25 embodiment does not assume that the surface of the
object exists on a projection point among the plural
projection points overlapping viewed from the
reference viewpoint like conventional methods for
obtaining the three-dimensional shape, but assumes

30 that the surface of the object exists on each
projection point with the existence probability. By
doing so, even when the reliability in distance
estimation is low, the surface of the object exists
with a probability on the projection point at which

35 the surface of the object actually exists. In this
case, when the image of the object viewed from the
virtual viewpoint is generated, a pixel, among

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points (pixels) of the generated image, having color
information or brightness information obtained by
mixing color information of projection point at
which the existence probability is low is rendered
5   vaguely, that is, a point on the object at which the
reliability in distance estimation is low is
rendered vaguely. As a result, discontinuous noise
that may occur when erroneous distance estimation is
performed can be made inconspicuous.
10   In this method, plural images having
different focusing degree are used for obtaining the
three-dimensional shape of the object. The
existence probability of each of the projection
points overlapping when viewed from the reference
15 viewpoint is determined based on the focusing degree
of points (corresponding points) on each image
corresponding to the projection points. Therefore,
there may be a case where more than one projection
points at which the existence probability is very
20 high are included in the plural projection points
overlapping when viewed from the virtual viewpoint
depending on the shape of the object or the position
relationship between the reference viewpoint and the
virtual viewpoint. In such a case, for example,
25 there is a fear that color information on a point of
the generated image exceeds a limit of an effective
color space when color information or brightness
information of each projection point are mixed in a
ratio according to the existence probability.
30 Therefore, the transparency may be set at the
projection point based on the existence probability
so that the mixing processing of the color
information can be performed based on a ratio
according to the transparency. By doing so, when
35 more than one projection points at which the
existence probability is high are included in the
plural projection points overlapping when viewed

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from the virtual viewpoint, contribution of color
information of a projection point far from the
virtual viewpoint to color information of a point on
the generated image can be decreased, wherein the
5 projection point far from the virtual viewpoint is a
projection point that is not visible from the
virtual viewpoint, for example.

This method does not perform processing
for obtaining an accurate geometrical model for
10 every shape of the object and for every point of the
object as performed in conventional generation
methods. Therefore, workload on the apparatus
(computer) that generates the image can be decreased.
By decreasing the workload on the apparatus that
15 generates the image, the image can be generated at
high speed even by an apparatus having low
processing performance like a generally used
personal computer.

In addition, when obtaining the three-
20 dimensional shape of the object, by using the images
taken from one viewpoint by changing the focusing
distance, the taking apparatus used for taking the
images can be downsized compared to a conventional
apparatus that takes the images from plural
25 viewpoints, so that the apparatus configuration can
be simplified. In this case, for example, by taking
the object using the polarizing binary optical
system including a material by which the focusing
distance changes according to the polarization
30 planes, two images having different focusing
distances can be taken from one viewpoint. In
addition, for example, by providing plural lenses of
difference focusing distances so as to take the
images while changing each lens at high speed, more
35 than two images having different focusing distances
can be taken from one viewpoint.

[Fourth embodiment]

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Next, the fourth embodiment of the present invention is described. The fourth embodiment mainly corresponds to claims 30-43. The fourth embodiment is characterized in that the existence
5　probability is obtained based on statistical processing (parameter fitting) for the evaluation reference value v_j. In figures for explaining the fourth embodiment, the same signs are assigned to components having the same function.
10　　　　　In the three-dimensional image display method of the fourth embodiment, the three-dimensional shape of the object is obtained from plural images obtained by taking the object under different taking conditions each other. Then, based
15　on the three-dimensional shape of the object, a three-dimensional image of the object is displayed on a display having plural display planes like the DFD. When obtaining the three-dimensional shape of the object, projection planes of the multi-layered
20　structure are set in a virtual three-dimensional space, and for points (projection points), on plural projection planes, that overlaps when viewed from the observer's viewpoint, color information or brightness information of each projection point, and
25　probability (existence probability) that the surface of the object exists on the projection point is determined. Then, when generating two-dimensional images to be displayed on the plural display planes based on the three-dimensional shape of the object,
30　the color information or brightness information and the existence probability are assigned to each point of the two-dimensional images. When displaying the image on the image display plane, each point of the two-dimensional image is displayed with brightness
35　according to the existence probability. By doing so, a part at which the reliability of estimation on distance of the surface of the object is low is

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displayed vaguely, so that a three-dimensional image that looks natural for the observer can be provided.
        (Embodiment 4-1)
                Figs.66-77 are schematic diagrams for
5   explaining the image generation method of the embodiment 4-1. Fig.66 is a flow diagram showing an example of the whole processing procedure. Figs.67 and 68 are diagrams showing an example of a method for setting the projection planes. Fig.69 is a
10 diagram for explaining a method for setting projection point series. Fig.70 is a flow diagram showing an example of processing procedure of steps for determining the color information and the existence probability of the projection point.
15 Figs.71-74 are diagrams for explaining a method for determining the existence probability. Figs.75-77 are diagrams for explaining a method for generating the two-dimensional images to be displayed on each image display plane.
20   The image generation method of this embodiment 4-1 is a method for generating images to be displayed on an image display means, like a DFD, for example, including plural image display planes overlapping in the depth direction from the
25 viewpoint of the observer. As shown in Fig.66, the method includes a step 101 of obtaining plural images by taking the object from different viewpoints, a step 102 of setting a viewpoint (reference viewpoint) of the observer who observes
30 the three-dimensional image, a step of 103 for obtaining the three-dimensional shape of the object from plural images, a step 104 of generating two-dimensional images to be displayed on each image display plane based on the three-dimensional shape
35 of the object obtained in the step 103, and a step 105 for providing the three-dimensional image of the object by displaying the two-dimensional images

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generated in the step 104 on each image display
plane.

    For generating images for displaying the
tree-dimensional image of the object by the DFD, for

5 example, using the image generation method of this
embodiment 4-1, images are obtained by taking the
object from different viewpoints (step 101). In
this step, the viewpoints from which the images are
taken may be arranged in a line or may be arranged

10 like an arc or on any curved line, or may be
arranged two-dimensionally on a plane or a curved
surface. In addition, although the obtained image
may be a color image or a clack and white image, the
color image in which each pixel on the image is

15 represented by color information using three-primary
colors of red (R), green (G) and blue (B) is
obtained in this embodiment 4-1.

    Next, after obtaining the images in the
step 1, the viewpoint of the observer who observes

20 the object to be displayed on the DFD is set (step
102). In this step, as to the viewpoint of the
observer, relative position relationship between the
viewpoint of the observer and a reference image
display plane in the plural image display planes,

25 such as a distance from the image display surface,
and direction of line of sight and the like are set.

    Next, after setting the viewpoint of the
observer in step 2, the three-dimensional shape of
the object appearing in the images are obtained from

30 the plural images obtained in the step 1 (step 103).
In the step 3, first, projection planes
$L_j(j=1,2,...,M)$ of the multi-layered structure are set
(step 10301). Then, next, the reference viewpoint R
for obtained the three-dimensional shape of the

35 object is set (step 10302). As the projection
planes L_j, plural planes parallel to the xy plane on
the virtual three-dimensional space are set as shown

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in Figs.67 and 68, for example. In addition, each projection plane L_j is set at each distance l_j from z=0 in a minus direction in the three-dimensional space as shown in Figs.67 and 68. The reference
5   viewpoint R is a viewpoint for obtaining the three-dimensional shape of the object, and can be set as any point in the three-dimensional space. Therefore, the reference viewpoint R is determined to be the viewpoint of the observer set in the step 2. In
10   addition, for example, a projection plane L_1 farthest from z=0 is regarded as an image display plane existing in the deepest place from the observer of the DFD, and the reference viewpoint R is set such that the distance from the projection
15   plane L_1 becomes the distance ld from the observer's viewpoint to the image display plane deepest in the DFD as shown in Fig.68.

Next, after setting the projection planes L_j and the reference viewpoint R in the step 10301
20   and the step 10302, projection points on the projection planes, and points (corresponding points), on the obtained images, corresponding to each projection point are set (step 10303). In this step, as shown in Fig.69, lines are drawn to plural
25   directions from the reference viewpoint R, and the projection points are set as each cross point of each line and each projection plane L_j. When estimating the distance of the surface of the object, since projection points at which the surface exists
30   are estimated from the plural projection points T_j on the same line, projection points T_j on the same line are dealt, as one, as projection point series s.

The corresponding point is a point G_{ij}, on the image plane of each camera, overlapping with the
35   viewpoint of the camera when viewing the viewpoint C_i of the camera from the projection point T_j, as shown in Fig.67 and 68. As shown in Fig.67, when

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setting a two-dimensional coordinate system (xy coordinate system) on each image, two-dimensional coordinates (x_{ij}, y_{ij}) of the corresponding point G_{ij} corresponding to the projection point $T_j(X_j, Y_j, Z_j)$

5   can be obtained by projecting the projection point T_j on a two-dimensional point of each image plane. This projection can be performed by using a 3 rows and 4 culumns projection matrix for projecting a point (X, Y, Z) in a three-dimensional space to a

10   point (x, y) in a two-dimensional plane. The relationship between the coordinates (x_{ij}, y_{ij}) of the corresponding point G_{ij} in the virtual three-dimensional space and the digital image coordinates (u, v) is as described so far.

15   In the the step 10303, the three-dimensional space coordinates (X_j, Y_j, Z_j) of the projection point T_j are associated with the digital image coordinates (u_{ij}, v_{ij}) of the corresponding point G_{ij}. The establishment of the association may

20   be performed by providing values of (X_j, Y_j, Z_j) in a table for every (u_{ij}, v_{ij}), or by setting values of (X_j, Y_j, Z_j) only for representative values of (u_{ij}, v_{ij}) so as to obtain other points by performing interpolation processing such as linear

25   interpolation, for example.
        In addition, although (u, v) take discrete values in the digital image coordinate system, it is assumed that (u, v) take continuous values unless otherwise specified in the following descriptions,

30   and it is assumed to perform proper discretization processing when accessing the two-dimensional array.
        After completing determining the projection point series, corresponding points and the like in the step 10303, next, the array (texture

35   array) for storing, information of the projection planes L_j, that is, the image that is to be texture-mapped on the projection planes L_j is kept(step

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10304). At this time, the array to be kept includes color information and existence probability for each pixel as texture information, corresponding to the position of the projection point T_j, by 8 bits, for

5   example.

Next, after keeping the array for storing information of the projection planes in the step 10304, color information and existence probability of each projection point T_j is determined (step

10   10305). In the step 10305, as shown in Fig.70, for example, double loop processing is performed in which processing for determining color information and the existence probability of each projection point T_j of projection point series is repeated for

15   every projection point series that are set. Then, first, the projection point series is initialized (step 10305a). Next, the projection point T_j on the projection point series is initialized to $j=1$, for example (step 10305b).

20   Next, the color information of the projection point T_j is determined (step 10305c). In the step 10305c, color information K_j of the projection point T_j is determined as an average value of color information K_i of corresponding

25   points G_i set in the step 10303, for example.

Next, the correlation degree Q_j of each point on the object that is appearing at each corresponding point $G_{ij}(i \in I)$ corresponding to the projection point T_j is obtained (step 10305d).

30   Assuming that a vector for representing the color information of the projection point T_j is K_j, and that a vector repressing the color information of the corresponding point G_{ij} is K_{ij}, the correlation degree Q_j can be obtained by the following equation

35   86.

[Equation 86]

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$$Q_j = \sum_{i \in I} \left(K_j - K_{ij} \right)^2$$

By obtaining the correlation degree Q_j using the equation 86, the correlation degree Q_j always becomes a positive value, and, the higher the correlation, the smaller the value is.

5

The equation 86 is an example method for obtaining the correlation degree Q_j, and the correlation degree Q_j can be obtained using equations other than the equation 86. In addition, for obtaining the correlation degree Q_j, not only

10 each one point of the projection point T_j and the corresponding point G_{ij} is considered, but also a small region including plural points near the projection point T_j and the corresponding point G_{ij} can be considered.

15

After obtaining the correlation degree Q_j at the step 10305d, the projection point T_j is updated, and it is checked whether processing of the step 10305c and the step 10305d has been performed

20 for every projection point on the projection point series that is a subject of processing (step 10305e). If there is any projection point for which the processing of the step 10305c and the step 10305d has not been performed, the step returns to the step

25 10305c to obtain the color information K_j and the correlation degree Q_j.

After obtaining the color information and the correlation degree Q_j for every projection point on the projection point series that is a subject of

30 processing, the color information K_j and the correlation degree Q_j are provided to each projection point T_j on the projection point series as shown in Fig.71. When correlation degrees Q_j of the projection points T_j are compared with each

35 other, only a correlation degree Q_m of a projection

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point T_m takes a distinctive small value, generally,
as shown in Fig.72A. In this case, it can be
estimated that the surface of the object exists on
the projection point T_m on the subject projection
5 point series, and the reliability is high.
           However, there my be a case where there is
no projection point at which the correlation degree
has the distinctive small value, as shown in Fig.72B
when the correlation degrees Q_j of each projection
10 point T_j on the projection point series are compared
depending on the shape of the object, the texture of
the surface, photographing conditions and the like.
In this case, even if the surface of the object is
estimated to exist at a projection point, the
15 reliability is low and there is a case the
estimation is erroneous. When the estimation is
erroneous, the effect appears as a large noise on
the generated image.
           Thus, a probability (existence
20 probability) β_j that the surface of the object
exists on the projection point T_j on the projection
point series is determined based on the correlation
degree Q_j of the projection point T_j. Although the
existence probability β_j can be directly obtained
25 from the correlation degree Q_j, when there is noise
on the obtained images so that the reliability of
the correlation degree Q_j is low, the existence
probability β_j is affected so that its reliability
is lowered. Thus, according to the image generation
30 method of this embodiment 4-1, an evaluation
reference value v_j used as a reference value of the
existence probability β_j is obtained (step 10305f).
It is necessary that the evaluation reference value
v_j satisfies the following equations 87 and 88.
35 [Equation 87]

$$0 \leq \beta_j \leq 1$$

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[Equation 88]

$$\sum_{j=1}^{M} \beta_j = 1$$

In addition, for defining the evaluation reference value v_j such that the higher the probability that
5   the surface of the object exists at the projection point T_j is, the closer to 1 the evaluation reference v_j becomes, the evaluation reference value $v_j (j \in J)$ can be calculated after performing conversion processing represented by the following
10   equations 89 and 90, for example, for the correlation degrees Q_j obtained for each projection point T_j on the projection point series.
    [Equation 89]

$$\widetilde{\beta}_j = \frac{1}{Q_j}$$

15   [Equation 90]

$$\beta_j = \frac{\beta_j}{\sum_{j=1}^{M} \widetilde{\beta}_j}$$

        Basically, the evaluation reference value v_j only needs to satisfy the equation 87 and the equation 88. Therefore, for the conversion
20   processing, equations other than the equation 89 and the equation 90 can be used.
        The evaluation reference value v_j of each projection point T_j calculated using the equations 89 and 90 can be used as the probability (existence
25   probability) that the surface of the object exists, as mentioned before. But, due to influences of noise on the obtained image, there is a case where

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reliability as the existence probability is not
sufficiently high. Therefore, next, statistical
processing (parameter fitting) for the evaluation
reference value v_j is performed by assuming a
5 probability distribution model of the object so as
to obtain a fitting function p(l) as shown in
Fig.73A, for example (step 10305g).
          When it is assumed that the probability
density distribution of the probability that the
10 object exists complies with normal distribution
(Gaussian distribution) for the distance l, the
fitting function p(l) of the evaluation reference
value v_j can be represented as the following
equation 91.
15   [Equation 91]

$$p(l) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{ -\frac{(l-\mu)^2}{2\sigma^2} \right\}$$

wherein μ is an average value of the existence
probability distribution, σ is dispersion of
existence probability distribution, and they are
20 represented as the following equation 92 and
equation 93 respectively.
    [Equation 92]

$$\mu = \sum_{j=1}^{M} \beta_j l_j$$

    [Equation 93]

$$\sigma^2 = \sum_{j=1}^{M} \left(\beta_j l_j - \mu \right)^2$$

25

After obtaining the fitting function p(l), the
probability β_j that the object exists at a distance
lp_j of each projection plane LP_1, that is, at each

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corresponding point T_j is determined based on the
function $p(l)$ (step 10305h).   The existence
probability β_j is determined using the following
equation 94, for example.

5   [Equation 94]

$$\gamma_j = \int_{l_j^-}^{l_j^+} p(l)dl$$

wherein l_j^- and l_j^+ respectively are a lower limit
and an upper limit of a distance that contributes to
the projection plane L_j as shown in Fig.73B, and can
10   be calculated in the following equation 95 and
equation 96.

[Equation 95]

$$l_j^- = \frac{l_{j-1} + l_j}{2}, \quad l_j^- = -\infty$$

[Equation 96]

$$l_j^+ = \frac{l_j + l_{j+1}}{2}, \quad l_M^+ = \infty$$

15

By performing the processing from the step 10305c to
the step 10305h, the color information K_j and the
existence probability β_j on each projection point T_j
on the projection point series are determined as
20   shown in Fig.74.   The values are stored in the area
kept in the step 10304.

As mentioned above, when the probability
density distribution that the object surface exists
on the projection point series can be assumed, by
25   obtaining the existence probability β_j based on the
fitting function $p(l)$ of the evaluation reference
value v_j, the effect of the noise on the taken image
can be decreased.

The equation 91 is an example of the
30   fitting function.   The parameter fitting can be also

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performed using various functions according to shape distribution of then object. For example, the parameter fitting can be performed using a Laplacian distribution function.

5   After storing the color information K_j and the existence probability β_j of each projection point T_j, the projection point series is updated and it is checked whether processing from the step 10305c to the step 10305h has been performed for

10   every projection point series determined in the step 10303 (step 10305i). When there is any projection point series for which processing from the step 10305c to the step 10305h has not been performed, the step returns to the step 10305b so that the

15   processing from the step 10305c to the step 10305h is repeated.

          Accordingly, after the processing from the step 10305c to the step 10305h are performed for every projection point series determined in the step

20   10303, the processing of the step 10305 (step 103) completes, so that the three-dimensional shape of the object can be obtained.

          By performing the processing of the step 103, as shown in Fig.74, for example, the texture

25   array of each projection point $T_j(j=1,2,\dots,M)$ on the projection point series stores the color information K_j and the existence probability β_j. That is, as to the three-dimensional shape of the object obtained by the three-dimensional image display method of the

30   present invention, the surface of the object exits not only on one projection point on the projection point series as is in the conventional method, but the surface of the object exits on each projection point.

35   In the image generation method of this embodiment 4-1, image of object viewed from the observer is generated based on the obtained three-

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dimensional shape of the object. In this embodiment
4-1, the generated images are displayed on each
image display plane of a display, such as the DFD,
having plural image display planes. The method for
5   generating the two-dimensional images is described
in this embodiment 4-1. In this case, after
completing the processing of the step 103, as shown
in Fig.66, the color information and the existence
probability of each projection point are converted
10 to color information and brightness distribution
coefficient of each point on the two-dimensional
image generation plane (step 104).

When generating the two-dimensional images
to be displayed on each image display plane in step
15 104, the viewpoint of the observer, plural two-
dimensional image generation planes, and the three-
dimensional shape of the object obtained in the step
103 are set, first. In this step, the two-
dimensional image generation planes $LD_n(n=1,2,…,N)$
20 are set such that they overlap with each other in
the depth direction from the viewpoint P of the
observer as shown in Fig.75, for example. In
addition, the distance ld_n from the viewpoint P of
the observer to the two-dimensional image generation
25 plane LDn is set such that it becomes the distance
set in the step 102. At this time, if the number of
projection planes L_j representing the three-
dimensional shape of the object and the placement
intervals are the same as the number of the two-
30 dimensional image generation planes LD_n and the
placement intervals, the three-dimensional shape of
the object is set such that the projection planes L_j
becomes the same as the two-dimensional image
generation planes LD_n, as shown in Fig.75, for
35 example. In this case, when the two-dimensional
image generation planes LD_n are planes for
generating the images displayed on the image display

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planes of the brightness modulation type DFD, it is
necessary to determine the color information KD_n and
the brightness distribution coefficient γ_n for each
point (display point) A_n, on the two-dimensional

5   image generation planes LD_n, that overlap viewed
from the viewpoint P of the observer. As shown in
Fig.75, when the projection planes L_j representing
the three-dimensional shape of the object are the
same as the two-dimensional image generation planes

10   LD_n, the color information KD_n of each display point
A_n is determined to be the color information K_j of
the projection point T_j on the projection plane L_j
that is overlapping the two-dimensional image
generation plane LD_n on which the display point A_n

15   exists. In addition, the brightness distribution
ratio γ_n of the display point A_n is determined to be
the existence probability β_j of the projection point
T_j on the projection plane L_j that is overlapping
the two-dimensional image generation plane LD_n.

20   After the color information KD and the brightness
distribution coefficient γ are determined for each
display point A on the two-dimensional image
generation surfaces LD_n, the images generated on the
two-dimensional image generation planes LD_n are

25   output and are displayed on the image display planes
of the actual DFD (step 105).
           However, it is not necessary that the
number and placement intervals of the projection
planes L_j for representing the three-dimensional

30   shape of the object are the same as the number and
placement intervals of the two-dimensional image
generation planes LD_n. Therefore, next, another
method for generating the two-dimensional images are
described in a case where the number and placement

35   intervals of the projection planes L_j for
representing the three-dimensional shape of the
object are not the same as the number and placement

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intervals of the two-dimensional image generation planes LD_n.

In this case, when the distance from a projection plane closest to the viewpoint P of the observer to a projection plane farthest from the viewpoint P is almost the same as the distance from a two-dimensional image generation plane closest to the viewpoint P to a two-dimensional image generation plane farthest from the viewpoint P, the projection planes L_j representing the three-dimensional shape of the object are set such that the projection plane L_1 farthest from the viewpoint P of the observer and the two-dimensional image generation plane LD_1 overlap. By doing so, color information and brightness distribution coefficient γ of each display point A on the two-dimensional image generation plane LD_1 farthest from the viewpoint P of the observer become the color information K and the existence probability β of each projection point T on the projection plane L_1 farthest from the viewpoint P of the observer.

Color information KD and brightness distribution coefficients γ of each display point A on the two-dimensional image generation planes LD each of which does not overlap any projection plane are determined in the following method.

As to the color information KD and brightness distribution coefficients γ of each display point A on the two-dimensional image generation planes LD each of which does not overlap any projection plane, color information K and existence probability β of each of projection points T, on the projection planes L, overlapping with the display point when viewed from the viewpoint P of the observer are assigned to a projection point A on the two-dimensional image generation plane LD closest with respect to the projection plane L. In

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this case, the color information KD of the display
point A is determined to be an average value of
assigned color information K of projection points T,
or to be color information L of the projection point

5　T, on the projection plane L, closest to the two-
dimensional image generation plane LD. The
brightness distribution coefficient γ is determined
to be a sum of pieces of assigned existence
probabilities β of each projection point T. In this

10　case, assuming that a set of projection planes L_j to
which the two-dimensional image generation plane LD_n
is the closest is $\{L_j | j \in \Gamma_n\}$, the brightness
distribution ratio γ_n of the display point A_n on the
two-dimensional image generation plane LD_n is

15　provided by the following equation 97 using the
existence probability β_j of the projection point T_j
of the projection plane L_j.
[Equation 97]

$$\gamma_h = \sum_{j \in \Gamma_n}^{M} \beta_j$$

20　　　　In the following, a case where position
relationship between the projection planes L_j and
the two-dimensional image generation surfaces LD_n is
as shown in Fig.77A is considered. Assuming that
color information K_j and each existence probability

25　β_j of each of projection points $T_j (j=1,2,3,4,5)$
overlapping with the display points A_1 and A_2 when
viewed from the viewpoint P of the observer are
assigned to a display point A on a two-dimensional
image generation surface that is closest from the

30　projection plane, color information and existence
probabilities of the projection points T_1, T_2 and T_3
are assigned to the display point A_1. In this case,
the color information of the display point A_1 may be
an average value of the color information K_1, K_2 and

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K_3 of the projection points T_1, T_2 and T_3, for
example, or may be the color information K_2 of the
projection point T_2 closest from the viewpoint of
the display point A_1. The brightness distribution
5   coefficient γ_1 of the display point A_1 is determined
to be a sum of the existence probabilities β_1, β_2
and β_3 of the projection points T_1, T_2 and T_3 using
the equation 91.

In the same way, color information and
10   existence probabilities of the projection points T_4
and T_5 are assigned to the two-dimensional image
generation surface LD_2. In this case, the color
information KD_2 of the display point A_2 may be an
average value of the color information K_4 and K_5 of
15   the projection points T_4 and T_5, or may be the color
information K_5 of the projection point T_5. The
brightness distribution coefficient γ_2 is determined
to be a sum of the existence probabilities β_4 and β_5
of the projection points T_4 and T_5 using the equation
20   91.

When the placement intervals of the two-
dimensional image generation planes LD_n and the
placement intervals of the projection planes L_j are
different, color information and existence
25   probability of the projection point on a projection
plane L_j existing between two successive two-
dimensional image generation planes LD_n and LD_{n+1} can
be distributed in a ratio of the distances of the
two two-dimensional image generation planes LD_n and
30   LD_{n+1}. In this case, assuming that a set of the
projection planes L_j between the two-dimensional
image generation planes LD_n and LD_{n+1} is $\{L_j | j \in \Gamma_n\}$,
the brightness distribution ratio γ_n of the display
point A_n on the two-dimensional image generation
35   plane LD_n can be calculated by the following
equation 98 using the existence probability β_j of
each projection points T_j.

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[Equation 98]

$$\gamma_h = \sum_{j \in \Gamma_n} w_{j,h}\, \beta_j$$

In the equation 98, $w_{j,n}$ is a coefficient indicating a degree of contribution of the projection plane L_j
5　to the two-dimensional image generation plane LD_n.

A case where projection planes L_1 and L_2 are set between the two-dimensional image generation planes LD_1 and LD_2 is considered as shown in Fig.77B, for example. In this case, assuming that distances
10　from the projection plane L_1 to the display planes LD_1 and LD_2 are B_1 and B_2 respectively, the degrees $w_{1,1}$ and $w_{1,2}$ of contribution of the projection plane L_1 to the two-dimensional image generation planes LD_1 and LD_2 can be provided by the following equation 99.

15　[Equation 99]

$$w_{1,1} = \frac{B_2}{B_1 + B_2}, \quad w_{1,2} = \frac{B_1}{B_1 + B_2}$$

In the same way, when distances from the projection plane L_2 to the display planes LD_1 and LD_2 are B_3 and B_4 respectively, the degrees $w_{2,1}$ and $w_{2,2}$ of
20　contribution of the projection plane L_2 to the two-dimensional image generation planes LD_1 and LD_2 can be provided by the following equation 100.

[Equation 100]

$$w_{2,1} = \frac{B_4}{B_3 + B_4}, \quad w_{2,2} = \frac{B_3}{B_3 + B_4}$$

25　As a result, each of the brightness distribution ratio γ_1 of the display point A_1 of the two-dimensional image generation plane LD_1 and the brightness distribution ratio γ_2 of the display point A_2 of the two-dimensional image generation
30　plane LD_2 is shown in the following equation 101.

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[Equation 101]

$$\gamma_1 = w_{1,1}\,\beta_1 + w_{2,1}\,\beta_2, \quad \gamma_2 = w_{1,2}\,\beta_1 + w_{2,2}\,\beta_2$$

As mentioned above, when obtaining the three-dimensional shape of the object, a shape is obtained

5   in which the probability (existence probability) β_j that the surface of the object exists on each projection point T_j is provided from the correlation degree Q_j of the projection point T_j on the projection point series. Then, the brightness

10   distribution coefficient of the display point A on the two-dimensional image generation plane LD is provided as the existence probability β_j. Accordingly, when there is no projection point having the correlation degree Q_j of a distinctive

15   value in the projection points T_j on the projection point series, so that reliability for estimation of the distance of the surface of the object is low, the surface of the object is represented vaguely on plural projection planes on the projection point

20   series. Then, the brightness distribution coefficient γ of points on the two-dimensional image generation plane LD is determined from the existence probability β of each projection point T_j. Accordingly, when the two-dimensional images

25   generated on the two-dimensional image generation planes are displayed on the actual image display planes so as to present the three-dimensional image of the object, the surface of the object is displayed vaguely on the projection point series in

30   which reliability for distance estimation is low and the existence probability β is dispersed to plural projection points. Therefore, a noise on the three-dimensional image displayed on the DFD becomes inconspicuous so that an image that looks natural

35   for the observer can be displayed.
        As described above, according to the image

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generation method of this embodiment 4-1, the three-dimensional image that looks natural for the observer can be displayed without obtaining the accurate three-dimensional shape of the object to be

5   displayed.

In addition, by obtaining the existence probability β_j by assuming probability density distribution of the probability that the surface of the object exists on the projection point series and

10   by performing statistical processing for the evaluation reference value v_j calculated from the correlation degree Q_j, deterioration of the reliability of the existence probability β_j due to noise on the obtained images can be decreased.

15   In addition, in the image generation method of this embodiment 4-1, although a case is described by taking an example in which a color image in which the point (pixel) is represented by color information using three primary color of red

20   (R), green (G) and blue (B) is obtained and the three-dimensional shape of the object is generated, the image to be obtained is not limited to the color image. In the image generation method of this embodiment 4-1, a black and white image in which the

25   point (pixel) is represented by brightness (Y) and color-difference (U,V) may be obtained to obtain the three-dimensional shape of the object. In the case when the image to be obtained is the black and white image, the three-dimensional shape can be obtained

30   by the procedure described in this embodiment 4-1 using the brightness information (Y) as information corresponding to the color information so that the two-dimensional images can be generated.

(Embodiment 4-2)

35   Figs.78-81 are schematic diagrams for explaining the image generation method of the embodiment 4-2. Fig.78 is a diagram showing

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relationship between the projection point and the corresponding point. Fig.79 is a flow diagram showing an example of steps for determining the color information and the existence probability of
5　the projection point. Figs.80 and 81 are diagrams for explaining a method for obtaining the existence probability.
　　　　　The basic procedure of the image generation method of this embodiment 4-2 is the same
10　as the image generation method of the embodiment 4-1. When generating the plural two-dimensional images to be displayed on the DFD, processing from the step 101 to the step 105 shown in Fig.66 are performed. The different point of the image generation method
15　of this embodiment 4-2 compared to the image generation method of the embodiment 4-1 is that plural images of different focusing distances are obtained instead of the plural images of different viewpoints in step 101, and the three-dimensional
20　shape of the object is obtained using the images having different focusing distances in the step 103.
　　　　　For generating the plural two-dimensional images for displaying the three-dimensional image of the object on the DFD using the image generation
25　method of the embodiment 4-2, plural images are taken from a viewpoint while changing the focusing distance, first. At this time, the plural images are taken using the polarizing binary optical system, a variable focus lens and the like, for example.
30　The image to be obtained may be a color image in the same way as the embodiment 4-1 or may be a black and white image. Next, as described in the embodiment 4-1, after setting the viewpoint of the observer (step 102), processing of the step 103 for obtaining
35　the three-dimensional shape of the object is performed.
　　　　　In the processing of the step 103, as

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described in the embodiment 4-1, projection planes
L_j (j=1,2,…,M) and the reference viewpoint R are set
first (step 10301, step 10302). Then, next, the
projection point series and the corresponding points

5   are set, and the array (area) for storing the
information of the projection plane is kept (step
10303, step 10304).

In the three-dimensional image display
method of this embodiment 4-2 in which the three-

10·   dimensional image of the object is displayed using
plural images having different focusing distances,
when setting the projection planes L_j in step 10301,
the planes are set such that the distances from the
viewpoint c of the camera are the same as the

15   focusing distances f_i (i=1,2,…,N) of the images taken
by the camera as shown in Fig.78, for example. Then,
in the step 10303, the corresponding points G_i
corresponding to the projection point T_j is
determined to be points, on images Img_i, overlapping

20   with the projection point T_j when viewing the
projection point T_j from the viewpoint C of the
camera. Methods for setting the projection point
series, and for associating the coordinates of the
projection point T_j with the digital image

25   coordinates of the corresponding point G_i are the
same as the methods described in the embodiment 4-1.
Thus, detailed descriptions are not provided here.

In addition, the processing for keeping
the area for storing the information of the

30   projection planes in the step 10304 is also the same
as that described in the embodiment 4-1. Thus,
detailed descriptions are not provided here.

Next, the color information and the
existence probability information of each projection

35   point T_j are determined using the obtained plural
images (step 10305). Also in the three-dimensional
image display method of this embodiment 4-2, in the

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step 10305, double loop processing is performed in
which processing for determining the color
information and the existence probability of each
projection point T_j on the projection point series

5   is repeated for every projection point series. Thus,
first, the projection point series is initialized
(step 10305a). Then, next, the projection point T_j
on the projection point series is initialized to j=1,
for example (step 10305b).

10   Next, the color information of the
projection point T_j is determined (step 10305c). In
the step 10305c, an average value of color
information of the corresponding points G_i set in
the step 10303 is determined to be the color

15   information K_j of the projection point T_j.
              Next, the focusing degree Q_j of the
projection point T_j is obtained based on degree
(focusing degree) by which focus is achieved for a
point, of the object, appearing on each

20   corresponding point G_i corresponding to the
projection point T_j (step 10305j). The focusing
degree of the projection point T_j can be determined
according to sharpness or blurriness at a point or a
small region on the image. As a calculation method

25   for the focusing degree, there are various methods
based on Depth from Focus theory or Depth from
Defocus theory. The focusing degree Q_j can be
obtained by comparing sizes of local spatial
frequency of each corresponding point G_i, for

30   example.
              The Depth from Focus theory or the Depth
from Defocus theory is a method for analyzing plural
images having different focusing distance to measure
the surface shape of the object. In the method, the

35   surface of the object is estimated to exist at a
distance corresponding to a focusing distance of an
image having the highest local spatial frequency

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among the images taken by changing the focusing
distance, for example. Thus, the focusing degree Q_j
of the projection point T_j is calculated using an
evaluation function of the local spatial frequency
5   represented by the following equation 102, for
example.

[Equation 102]

$$Q = \frac{1}{D} \sum_{x=x_i}^{x_f} \sum_{y=y_i}^{y_f} \left\{ \sum_{p=-L_c}^{L_c} \sum_{q=-L_r}^{L_r} |f(x,y) - f(x+p, y+q)| \right\}$$

wherein f indicates a gray scale of a pixel, D
10   indicates a constant for normalization that is a
number of all pixels, (-Lc, -Lr)-(Lc, Lr) and (xi,
yi)-(xf, yf) indicate small regions for performing
distribution evaluation and smoothing respectively.
         The equation 102 is one example for a
15   method for obtaining the focusing degree Q_j, and the
focusing degree Q_j can be obtained by using
equations other than the equation 102.
         After obtaining the focusing degree Q_j by
the step 10305j, the projection point T_j is updated,
20   and it is checked whether processing of the steps
10305c and 10305j are performed for every projection
point on the projection point series that is a
subject for processing (step 10305e). When there is
any projection point for which the processing of the
25   steps 10305c and 10305j has not been performed, the
step returns to the step 10305c so that the color
information K_j and the focusing degree Q_j are
obtained.
         When the color information and the
30   focusing degree Q_j are obtained for every projection
point on the projection point series that is a
subject of processing, color information K_j and the
focusing degree Q_j are provided for each projection
point T_j on the projection point series as shown in

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Fig.80.   The focusing degree Q_j of the projection
point T_j is a degree corresponding to the
correlation degree used for determining the
existence probability β in the embodiment 4-1.
5   There my be a case where there is no projection
point at which the focusing degree has the
distinctive small value when the focusing degrees Q_j
of each projection point T_j on the projection point
series are compared depending on the shape of the
10 object, the texture of the surface, photographing
conditions and the like.   In this case, even if the
surface of the object is estimated to exist at a
projection point, the reliability is low and there
is a case the estimation is erroneous.   When the
15 estimation is erroneous, the effect appears as a
large noise on the generated image.

Thus, according to the three-dimensional
image display method of this invention, next, as
shown in Fig.81, the probability (existence
20 probability) β_j that the surface of the object
exists on each projection point T_j on the projection
point series is determinewd.   In this case, as
described in the embodiment 4-1, the existence
probability β_j is determined after performing
25 statistical processing for the evaluation reference
value v_j to prevent deterioration of the reliability
due to the noise of the obtained images (step
10305f).   For calculating the evaluation reference
value v_j in the step 10305f, it is necessary that
30 the evaluation reference value v_j satisfies the
equations 87 and 88.   Thus, in this embodiment 4-2,
the evaluation reference value v_j of the projection
point T_k is determined using the equation 103, for
example.

35 [Equation 103]

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$$\beta_k = \frac{Q_k}{\displaystyle\sum_{j=1}^{M} Q_j}$$

It is only necessary that the evaluation
reference value v_j satisfies the conditions of the
equations 87 and 88. Therefore, the evaluation
5   reference value v_j can be determined using equations
other than the equation 97.
After calculating the evaluation reference
value v_j in step 10305f, next, parameter fitting is
performed according to the before-mentioned
10   procedure, so that the existence probability β_j of
each projection point T_j is determined as shown in
Fig.81 (steps 10305g and 10305h)
After determining the existence
probability β_j of each projection point T_j in the
15   step 10305h, the color information K_j and the
existence probability β_j of each projection point T_j
are stored in the area kept in the step 10304.
After storing the color information K_j and
the existence probability β_j of each projection
20   point T_j, the projection point series is updated and
it is checked whether processing from the step
10305c to the step 10305h has been performed for
every projection point series determined in the step
10303 (step 10305i). When there is any projection
25   point series for which processing from the step
10305c to the step 10305h has not been performed,
the step returns to the step 10305b so that the
processing from the step 10305c to the step 10305h
is repeated.
30   Accordingly, after the processing from the
step 10305c to the step 10305h are performed for
every projection point series determined in the step
10303, the processing of the step 10305 completes,

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so that the three-dimensional shape of the object
can be obtained. Then, after obtaining the three-
dimensional shape of the object by the processing of
the step 103, color information and the brightness

5   distribution coefficient γ of the display point A on
the two-dimensional image generation plane LD are
determined based on the three-dimensional shape of
the object, so as to generate the two-dimensional
images to be displayed on the plural overlapping

10   image display planes such as the DFD according to
the same procedure as the embodiment 4-1 (step 104).
Then, by displaying the generated images on actual
image display planes (step 105), the three-
dimensional image of the object can be presented.

15   Also in the three-dimensional image
display method of this embodiment 4-2, like the
three-dimensional image display method of this
embodiment 4-1, when there is no projection point
having the focusing degree Q_j of a distinctive value

20   in the projection points T_j on the projection point
series, so that reliability for estimation of the
distance of the surface of the object is low, the
surface of the object is represented vaguely on
plural projection planes on the projection point

25   series. Then, the brightness distribution
coefficient γ of points on the two-dimensional image
generation plane LD is determined from the existence
probability β of each projection point T_j.
Accordingly, when the two-dimensional images

30   generated on the two-dimensional image generation
planes are displayed on the actual image display
planes so as to present the three-dimensional image
of the object, the surface of the object is
displayed vaguely on the projection point series in

35   which reliability for distance estimation is low and
the existence probability β is dispersed to plural
projection points. Therefore, a noise on the three-

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dimensional image displayed on the DFD becomes
inconspicuous so that an image that looks natural
for the observer can be displayed.

5   As described above, according to the image
generation method of this embodiment 4-1, the three-
dimensional image that looks natural for the
observer can be displayed without obtaining the
accurate three-dimensional shape of the object to be
displayed.

10   In addition, also in the case of the image
generation method of this embodiment 4-2, the image
to be obtained may be either of the color image or a
black and white image. When using the black and
white image, processing described in this embodiment

15   4-2 is performed using the brightness information
(Y) as the information corresponding to the color
information.

(Embodiment 4-3)

Figs.82-84 are schematic diagrams for

20   explaining an arbitrary viewpoint image generation
method of the embodiment 4-3 according to the
present invention. Fig.82 is a flow diagram showing
an example of the whole processing procedure.
Fig.83 is a diagram for explaining the principle of

25   rendering. Figs.84A and 84B are flow diagrams
showing processing procedure for converting the
existence probability to the transparency.

In the embodiments 4-1 and 4-2, although a
method for generating the two-dimensional images to

30   be displayed on each image display plane of the
apparatus having plural image display planes like
the DFD using the three-dimensional shape of the
object obtained in the step 103 is taken as an
example, use of the three-dimensional shape of the

35   object is not limited to that, but it can be also
used for generating two-dimensional images of the
object viewed from arbitrary viewpoints. In this

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case, the difference compared to the embodiments 4-1
and 4-2 is that rendering is performed after the
step 103, that is, processing of step 106 for
generating the two-dimensional image of the object
5   viewed from the observer's viewpoint from the three-
dimensional shape. Since the processing from the
step 101 to step 103 in which the three-dimensional
shape of the object is obtained is as described in
the embodiments 4-1 and 4-2, it is not described in
10   detail.

        In the step 11 for rendering in the
arbitrary viewpoint image generation method of this
embodiment 4-3, the color information of each point
(pixel) on the arbitrary viewpoint image to be
15   displayed is determined by performing mixing
processing for color information K_j of projection
points $T_j (j=1,2,…,M)$ overlapping with a point A on
the arbitrary viewpoint image as shown in Fig.83,
for example. Mixing processing for color
20   information using the transparency α_j is performed
as described in the embodiment 2-2 and the like in
the second embodiment.

        Also in the method for generating the
arbitrary viewpoint image of this embodiment 4-3,
25   after performing the step 10305h for determining the
existence probability β_j, processing for converting
the existence probability v_j to the transparency α_j
is performed as shown in Fig.84A, for example (step
107).

30   In the processing for converting the
existence probability v_j to the transparency α_j, the
projection point T_j is initialized to j=M first as
shown in Fig.84B, for example (step 107a). Next, β_M
is substituted to transparency α_M of the projection
35   point T_M such that $\alpha_M=\beta_M$ (step 107b).

        Next, the value of the argument j is
updated to j=j-1 (step 107c). Then, it is

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determined whether the transparency α_{j+1} is 1 (step
107d). When transparency $\alpha_{j+1} \neq 1$, the transparency α_j
is obtained from the equation 104, for example (step
107e).

5 [Equation 104]

$$\alpha_j = \frac{1}{\displaystyle\prod_{m=j+1}^{M}(1-\alpha_m)} \beta_j$$

When the transparency α_{j+1} is 1, 1 is substituted
into α_j ($\alpha_j=1$), for example (step 107f). When
obtaining the transparency α_j in the step 107e, the
10 equation is not limited to the equation 104, and
other equations can be used. In addition, although
detailed descriptions are not provided, since any
value can be substituted into the transparency α_j
actually in step 107e, a value other than 1 may be
15 substituted into the transparency α_j.

Next, it is determined whether processing
from the step 107d to the step 107f has been
performed up to the argument j=1 (step 107g). When
the processing has not been performed, the
20 processing is repeated after returning to the step
107c.

After performing the processing from the
step 107d to the step 107f up to the argument j=1,
processing for converting the existence probability
25 v_j of the projection point T_j overlapping with the
point A on the image surface viewed from the
observer's viewpoint P to the transparency α_j
completes. After that, mixing processing using the
equation 62 and the equation 63 is performed in the
30 rendering step 104 to obtain the color information
D_M on the point A of the arbitrary viewpoint image.
Then, by performing the processing for every point
(pixel) on the arbitrary viewpoint image, the

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arbitrary viewpoint image from the observer's
viewpoint can be obtained.

    In addition, also in the case of the image
generation method of this embodiment 4-3, the image
5 to be obtained may be either of the color image or a
black and white image. When using the black and
white image, after obtaining the three-dimensional
shape of the object by performing processing
described in the embodiment 4-1 using the brightness
10 information (Y) as the information corresponding to
the color information, the virtual viewpoint image
can be generated according to the procedure
described in this embodiment 4-3.
    (Embodiment 4-4)
15   Figs.85-89 are schematic diagrams showing
general configurations of an image generation
apparatus this embodiment 4-4 according to the
present invention. Figs.85 and 86 are block
diagrams showing a configuration example of the
20 image generation apparatus. Figs.87 and 88 are
diagrams showing a configuration example of an image
display system using the image generation apparatus.
    In Figs.85 and 86, 2 indicates the three-
dimensional image generation apparatus, 201
25 indicates an object image obtaining means, 202
indicates a observer viewpoint setting means, 203
indicates a projection plane etc. setting means, 204
indicates a texture array keeping means, 205
indicates a color information/existence probability
30 determination means, 206 indicates a projection
plane information – display plane information
conversion means, 207 indicates an image output
means, 208 indicates a rendering means, 3 indicates
an image display means, 4 indicates an object image
35 taking means, and 5 indicates an observer viewpoint
input means.
    The image generation apparatus 2 in this

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embodiment 4-4 is an apparatus for obtaining the three-dimensional shape of the object according to the procedure described in the embodiments 4-1 and 4-2, and generating the two-dimensional images to be
5 displayed on each image display plane of the image display means 3 like the DFD having plural overlapping image display planes, and the image of the object viewed from arbitrary viewpoints. As shown in Fig.85, for example, the apparatus for
10 generating images to be displayed on the DFD includes the object image obtaining means 201 for obtaining plural object images taken under different photographing conditions, the observer viewpoint setting means 202 for setting a viewpoint of the
15 observer who observes a generated image, the projection plane etc. setting means 203 for setting projection planes, projection point series, projection points, corresponding points and the like for determining the existence probability, the
20 texture array keeping means 204 for keeping an area for storing color information and existence probability of points (projection points) on the projection plane, the color information/existence probability determination means 205 for determining the color information of the projection points and
25 the probability (existence probability) that the object exist at the projection points, the projection plane information - display plane information conversion means 206 for converting the color information and the existence probability
30 information of the projection point to color information and existence probability of a point of the two-dimensional image e to be displayed on the image display plane, and the image output means 207. An image output from the image output means 207 is
35 displayed by the image display means 3 such as the DFD including plural overlapping display planes.

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In addition, as described in the
embodiment 4-3, in the apparatus for generating the
image of the object viewed from the arbitrary
viewpoint, the rendering means 208 is provided
5 instead of the projection plane information –
display plane information conversion means 206 as
shown in Fig.86. Although not shown in the figure,
the apparatus may be configured to include both of
the projection plane information – display plane
10 information conversion means 206 and the rendering
means 208 and to generate a specified image using
either one of the means according to an instruction
from the observer.

      The object image obtaining means 201
15 obtains the images of the object taken by the object
image taking means 4. The object image taking means
4 may be a taking means including plural cameras at
plural viewpoints, or may be a taking means that can
take images having different focal positions from
20 one viewpoint. In this case, when the object image
taking means 4 takes images having different focal
positions from one viewpoint, the polarizing binary
optical system (refer to document 12, for example)
or a variable focus lens (refer to document 13, for
25 example) can be used. In addition, images can be
taken while switching plural lenses having different
focal positions at high speed.

      The observer viewpoint setting means 202
sets distance and the like between the observer's
30 viewpoint and the image display plane of the image
display means 3 based on information input using the
viewpoint information input means 5 such as the
mouse or a keyboard, by the observer for example.
The viewpoint information input means 5 may be a
35 means for detecting posture or line of sight of the
observer so as to input information according to the
posture or the line of sight.

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The projection plane etc. setting means 203 sets parallel projection planes L_j, projection point series, corresponding points and the like as described in the embodiments 4-1 and 4-2.

5   The texture array keeping means 204 keeps the area for the color information K_j and the existence probability β_j of each projection point T_j on each projection plane in a memory provided in the apparatus, for example, as descried in the
10   embodiments 4-1 and 4-2.

The color information/existence probability determination means 205 determines the color information from the projection point T_j and corresponding points G_{ij} on the image, and determines
15   the probability β_j that the surface of the object exists on the projection point T_j as descried in the embodiments 4-1 and 4-2.

The projection plane information - display plane information conversion means 207 converts the
20   color information and the existence probability of the projection plane into color information and the brightness distribution ratio of a point (display point) on the two-dimensional image to be displayed on each image display plane of the image display
25   means as described in the embodiment 4-1. In the case when the rendering means 208 is provided instead of the projection plane information - display plane information conversion means 206, color information of each point on images to be
30   generated are determined based on the equation 59, or the relationship of the equation 62 and the equation 63 as described in the embodiment 4-3.

The image generation apparatus 2 in this embodiment 4-4 generates the images to be displayed
35   on the DFD according to the procedure described in the embodiment 4-1 and the embodiment 4-2, for example. That is, the three-dimensional image

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generation apparatus 2 does not need to perform
processing for obtaining the accurate three-
dimensional shape of the object as was performed in
the conventional technology. Therefore, even by an
5   apparatus that does not have high processing ability
can generate the images to be displayed on the DFD
easily and at high speed.
        The image generation apparatus 2 of this
embodiment 4-4 can be also realized by a computer
10 and a program executed by the computer, for example.
In such as case, a program describes instructions
corresponding to the processing procedure described
in the embodiment 4-1, or instructions corresponding
to the processing procedure described in the
15 embodiment 4-2 is executed on the computer. In
addition, the program can be provided by a recording
medium that is magnetic, electrical or optical, or
can be provided via a network such as the Internet.
        In addition, the image display system
20 using the image generation apparatus 2 of this
embodiment 4-4 can be considered to be configured as
shown in Fig.87, for example. In the configuration,
the object image taking means 4 may be placed at a
place near the space where the observer User
25 observes the image display means (DFD) 3, or may be
placed at a place geographically apart. When the
object image taking means 4 is placed at the
geographically apart place, the taken image can be
transferred to the three-dimensional image
30 generation apparatus 2 using a network such as the
Internet.
        In addition, as shown in Fig.87, the image
display system using the image generation apparatus
2 of this embodiment 4-4 can be applied not only to
35 a case where an observer User observes an object Obj
but also to a bi-directional communication system
such as TV phone and TV conference. In the case,

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spaces in which the observers UserA and UserB exist
are respectively provided with image generation
apparatuses 2A and 2B, image display means (DFDs) 3A
and 3B, object image taking means 4A and 4B, and
5   reference viewpoint setting means 5A and 5B as shown
in Fig.88, for example. Then, for example, by
connecting between the image generation apparatuses
placed at the spaces where the observers UserA and
UserB exist by the network 6 such as the Internet,
10   the observer UserA can observe, by the image display
means 3A, the three-dimensional image of the
observer UserB generated from the image taken by the
object image taking means 4B. In the same way, the
observer UserB can observe, by the image display
15   means 3B, the three-dimensional image of the
observer UserA generated from the image taken by the
object image taking means 4A.
       In addition, it is not necessary both of
the image generation apparatuses 2A and 2B are
20   configured as shown in Fig.88 for applying to such
bi-directional communication system, either one of
the image generation apparatuses 2A and 2B can be a
general communication terminal that does not include
the configuration means shown in Fig.86. In
25   addition, each configuration means shown in Fig.86
may be distributed to the image generation
apparatuses 2A and 2B.
       In addition, as shown in Fig.88, if
another image generation apparatus 2C is provided on
30   the network 6, the three-dimensional image of the
object to be displayed on the image display means
(DFD) 3A and 3B can be obtained using the image
generation apparatus 2C on the network 6 even when
the image generation apparatuses 2A and 2B are not
35   placed at the spaces where the observers UserA and
UserB exists.
       In addition, in Figs.87 and 88, although a

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system is shown in which the object image taking
means 4 includes plural cameras, the number of
cameras may be one for generating the display image
as shown in Fig,89, for example, when obtaining the
5 three-dimensional shape of the object from images
having different focusing distances as described in
the embodiment 4-2.

　　　As mentioned above, although the present
invention is described concretely based on
10 embodiments, the present invention is not limited to
the specifically disclosed embodiments, and
variations and modifications may be made without
departing from the scope of the invention.

　　　For example, although a method for
15 displaying the three-dimensional image of the object
based on images of different viewpoints is described
in the embodiments 4-1, and a method for displaying
the three-dimensional image of the object based on
images having different focusing distances is
20 described in the embodiment 4-2, the three-
dimensional image of the object can be displayed by
combining these methods. In this case, the
correlation degree is obtained from corresponding
points of images of different viewpoints with
25 respect to a projection point T_j, the local space
frequency is obtained from corresponding points of
images taken by changing focal positions from a
viewpoint, and the existence probability β_j is
obtained by combining them. By doing so, the
30 reliability of the existence probability β_j
increases so that an image that looks natural for
the observer can be displayed.

　　(Effects of the fourth embodiment)

　　　In the image generation method of the
35 fourth embodiment, when obtaining the three-
dimensional shape of the object, as mentioned before,
plural projection planes are set, and the

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probability (existence probability) that the surface
of the object exists on the projection point is
provided to each of the points (projection points),
on each projection plane, overlapping when viewed
5   from the reference viewpoint. That is, the method
of this embodiment does not assume that the surface
of the object exists on a projection point in the
plural projection points overlapping viewed from the
reference viewpoint like conventional methods for
10   obtaining the three-dimensional shape, but assumes
that the surface of the object exists on each
projection point with the existence probability. In
addition, when determining the existence probability,
statistical processing is performed on the
15   evaluation reference value that is calculated from
the correlation degree or the focusing degree so
that the existence probability of the object is
generated from the evaluation reference value on
which the statistical processing has been performed.
20   At this time, in the statistical processing, a
probability distribution model of the object is
assumed, so that the fitting function of the
evaluation reference value of each projection point
is obtained, and the existence probability of each
25   projection point is determined from that.
        By doing so, when viewing a direction from
the reference viewpoint, even when the reliability
for estimating a distance (projection point) at
which the object surface exists is low, the surface
30   of the object exists with a probability on the
projection point at which the surface of the object
actually exists. As a result, by generating the
image of the object viewed from the viewpoint of the
observer based on the three-dimensional shape of the
35   object obtained according to the procedure,
discontinuous noise that may occur when erroneous
distance estimation is performed can be made

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inconspicuous. In addition, by determining the
existence probability by performing the statistical
processing for the evaluation reference value,
deterioration of the reliability of the existence
5 probability due to effects of noise of the obtained
images can be decreased.

In addition, according to this embodiment,
even by an apparatus having low processing
performance such a generally used personal computer,
10 each two-dimensional image can be generated at high
speed.

[Fifth embodiment]

Next, the fifth embodiment of the present
15 invention is described. The fifth embodiment mainly
corresponds to claims 44-53. In the fifth
embodiment, the three-dimensional shape of the
object is obtained from plural images obtained by
taking the object under different taking conditions.
20 Then, the three-dimensional image of the object is
displayed on a display, like a DFD, including plural
display planes based on the three-dimensional shape
of the object. In the fifth embodiment, processing
of the parameter fitting described in the fourth
25 embodiment is not performed. In figures for
explaining the fifth embodiment, the same signs are
assigned to components having the same function.

When obtaining the three-dimensional shape
of the object, projection planes of the multi-
30 layered structure are set in a virtual three-
dimensional space, and for points (projection
points), on plural projection planes, that overlap
when viewed from the observer's viewpoint, color
information or brightness information of each
35 projection point, and probability (existence
probability) that the surface of the object exists
on the projection point are determined. Then, when

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generating two-dimensional images to be displayed on
the plural display planes based on the three-
dimensional shape of the object, the color
information or brightness information and the
5   existence probability are assigned to each point of
the two-dimensional images. When displaying the
image on the image display plane, each point of the
two-dimensional image is displayed with brightness
according to the existence probability. By doing so,
10   a part at which the reliability of estimation on
distance of the surface of the object is displayed
vaguely, so that a three-dimensional image that
looks natural for the observer can be provided.
        (Embodiment 5-1)
15   Figs.90-100 are schematic diagrams for
explaining the three-dimensional image generation
method of the embodiment 5-1. Fig.90 is a flow
diagram showing an example of the whole processing
procedure. Figs.91 and 92 are diagrams showing an
20   example of a method for setting the projection plane.
Fig.93 is a diagram for explaining a method for
setting projection point series. Fig.94 is a flow
diagram showing an example of processing procedure
of steps for determining the color information and
25   the existence probability of the projection point.
Figs.95-97 are diagrams for explaining a method for
determining the existence probability. Figs.98-100
are diagrams for explaining a method for generating
the two-dimensional images to be displayed on each
30   image display plane.
        The three-dimensional image generation
method of this embodiment 5-1 is a method includes,
as shown in Fig.90, for example, a step 101 of
obtaining plural images by taking the object from
35   different viewpoints, a step 102 of setting a
viewpoint (reference viewpoint) of the observer who
observes the three-dimensional image, a step 103 for

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obtaining the three-dimensional shape of the object
from plural images, a step 104 of generating two-
dimensional images to be displayed on each image
display plane based on the three-dimensional shape
5   of the object obtained in the step 103, and a step
105 for providing the three-dimensional image of the
object by displaying the two-dimensional images
generated in the step 104 on each image display
plane.
10   For displaying the tree-dimensional image
of the object on the DFD using the image generation
method of this embodiment 5-1, images are obtained
by taking the object from different viewpoints (step
101). In this step, the viewpoints from which the
15   images are taken may be arranged in a line or may be
arranged like an arc or on any curved line, or may
be arranged two-dimensionally on a plane or a curved
surface. In addition, although the obtained image
may be a color image or a black and white image, ot
20   is assumed that the color image in which each pixel
on the image is represented by color information
using three-primary colors of red (R), green (G) and
blue (B) is obtained in this embodiment 5-1.
            Next, after obtaining the images in the
25   step 101, the viewpoint of the observer who observes
the object to be displayed on the DFD is set (step
102). In this step, as to the viewpoint of the
observer, relative position relationship between the
viewpoint of the observer and a reference image
30   display plane in the plural image display planes,
such as a distance from the image display plane, and
direction of line of sight and the like are set.
            Next, after setting the viewpoint of the
observer in step 102, the three-dimensional shape of
35   the object appearing in the images is obtained from
the plural images obtained in the step 101 (step
103). In the step 3, first, projection planes

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$L_j (j=1,2,…,M)$ of the multi-layered structure are set
(step 10301). Then, next, the reference viewpoint R
for obtained the three-dimensional shape of the
object is set (step 10302). As the projection
5 planes L_j, plural planes parallel to the xy plane on
the virtual three-dimensional space are set as shown
in Fig.91, for example. In addition, each
projection plane L_j is set at a distance l_j from z=0
in a minus direction in the three-dimensional space.
10 The reference viewpoint R is a viewpoint for
obtaining the three-dimensional shape of the object,
and can be set as any point in the three-dimensional
space. Therefore, the reference viewpoint R is
determined to be the viewpoint of the observer set
15 in the step 102. In addition, for example, a
projection plane L_1 farthest from z=0 is regarded as
an image display plane existing in the deepest place
from the observer of the DFD, and the reference
viewpoint R is set such that the distance from the
20 projection plane L_1 becomes the distance ld from the
observer's viewpoint to the image display plane
deepest in the DFD.

 Next, after setting the projection planes
L_j and the reference viewpoint R in the step 10301
25 and the step 10302, projection points on the
projection planes, and points (corresponding points),
on the obtained images, corresponding to each
projection point are set (step 10303). In this step,
lines are drawn to plural directions from the
30 reference viewpoint R, and the projection point is
set as a cross point of each line and each
projection plane L_j as shown in Fig.93. When
estimating the distance of the surface of the object,
since a projection point at which the object surface
35 exists is estimated from the plural projection
points T_j on the same line, projection points T_j on
the same line are dealt, as one, as projection point

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series s.

The corresponding point is a point G_{ij}, on the image plane of each camera, overlapping with the viewpoint of the camera when viewing the viewpoint

5　C_i of the camera from the projection point T_j, as shown in Figs.91 and 92. As shown in Fig.91, when setting a two-dimensional coordinate system (xy coordinate system) on each image plane, two-dimensional coordinates (x_{ij}, y_{ij}) of the

10　corresponding point G_{ij} corresponding to the projection point $T_j (X_j, Y_j, Z_j)$ can be obtained by projecting the projection point T_j on a two-dimensional point of each image plane. This projection can be performed by using a 3 rows and 4

15　columns projection matrix for projecting a point (X, Y, Z) in a three-dimensional space to a point (x, y) in a two-dimensional plane. The relationship between the coordinates (x_{ij}, y_{ij}) of the corresponding point G_{ij} in the virtual three-

20　dimensional space and the digital image coordinates (u, v) is as described so far.

In the step 10303, the coordinates (X_j, Y_j, Z_j) of the projection point T_j are associated with the digital image coordinates (u_{ij}, v_{ij}). The

25　establishment of the association may be performed by providing values of (X_j, Y_j, Z_j) in a table for every (u_{ij}, v_{ij}), or by setting values of (X_j, Y_j, Z_j) only for representative values of (u_{ij}, v_{ij}) so as to obtain other points by performing interpolation processing

30　such as linear interpolation, for example.

In addition, although (u, v) take discrete values in the digital image coordinate system, it is assumed that (u, v) take continuous values unless otherwise specified in the following descriptions,

35　and it is assumed to perform proper discretization processing when accessing the two-dimensional array.

After determining the projection point

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series, corresponding points and the like in the
step 10303, the array for storing, information of
the projection plane L_j, that is, the image that is
to be texture-mapped on the projection plane L_j is

5 kept (step 10304). At this time, the array to be
kept includes color information and existence
probability information for each pixel, by 8 bits
for example, as texture information corresponding to
the position of the projection point T_j.

10 Next, after keeping the array for storing
information of the projection plane in the step
10304, color information and existence probability
of each projection point T_j is determined (step
10305). In the step 10305, as shown in Fig.94, for

15 example, double loop processing is performed in
which processing for determining color information
and the existence probability of each projection
point T_j of projection point series is repeated for
every projection point series that are set. Then,

20 first, the projection point series is initialized
(step 10305a). Next, the projection point T_j on the
projection point series is initialized to $j=1$, for
example (step 10305b).

Next, the color information of the

25 projection point T_j is determined (step 10305c). In
the step 10305c, color information K_j of the
projection point T_j is determined as an average
value of color information K_i of corresponding
points G_i set in the step 10303, for example.

30 Next, the correlation degree Q_j of each
point on the object that is appearing at each
corresponding point $G_{ij}(i \in I)$ corresponding to the
projection point T_j is obtained (step 10305d).
Assuming that a vector for representing the color

35 information of the projection point T_j is K_j, and
that a vector repressing the color information of
the corresponding point G_{ij} is K_{ij}, the correlation

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degree Q_j can be obtained by the following equation 105.

[Equation 105]

$$Q_j = \sum_{i \in I} \left(K_j - K_{ij} \right)^2$$

5　By obtaining the correlation degree Q_j using the equation 105, the correlation degree Q_j always becomes a positive value, and, the higher the correlation, the smaller the value is.

The equation 105 is an example method for
10　obtaining the correlation degree Q_j, and the correlation degree Q_j can be obtained using equations other than the equation 86.　In addition, for obtaining the correlation degree Q_j, not only each one point of the projection point T_j and the
15　corresponding points G_{ij} is considered, but also a small region including plural points near the projection point T_j and the corresponding point G_{ij} can be considered.

After obtaining the correlation degree Q_j
20　at the step 10305d, the projection point T_j is updated, and it is checked whether processing of the step 10305c and the step 10305d has been performed for every projection point on the projection point series that is a subject of processing (step 10305e).
25　If there is any projection point for which the processing of the step 10305c and the step 10305d has not been performed, the step returns to the step 10305c to obtain the color information K_j and the correlation degree Q_j.
30　After obtaining the color information and the correlation degree Q_j for every projection point on the projection point series that is a subject of processing, the color information K_j and the correlation degree Q_j are provided to each
35　projection point T_j on the projection point series

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as shown in Fig.95.   When correlation degrees Q_j of the projection points T_j are compared with each other, only a correlation degree Q_m of a projection point T_m takes a distinctive small value, generally,
5   as shown in Fig.96A.   In this case, it can be estimated that the surface of the object exists on the projection point T_m on the subject projection point series, and the reliability is high.
However, as described in previous
10   embodiments, there may be a case where there is no projection point at which the correlation degree has the distinctive small value, as shown in Fig.96B when the correlation degrees Q_j of each projection point T_j on the projection point series are compared
15   depending on the shape of the object, the texture of the surface, photographing conditions and the like. In this case, even if the surface of the object is estimated to exist at a projection point, the reliability is low and there is a case the
20   estimation is erroneous.   When the estimation is erroneous, the effect appears as a large noise on the generated image.
Thus, according to the image generation method of the present invention, next, the
25   probability (existence probability) β_j that the object surface exists at the projection point T_j on the projection point series is obtained (step 10305f).   It is necessary that the existence probability β_j satisfies the following equations 106
30   and 107.
[Equation 106]

$$0 \le \beta_j \le 1$$

[Equation 107]

$$\sum_{j=1}^{M} \beta_j = 1$$

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In addition, for defining the existence probability β_j such that the higher the probability that the surface of the object exists at the projection point T_j is, the closer to 1 the existence probability β_j

5   is, the existence probability β_j $(j \in J)$ can be calculated after performing conversion processing represented by the following equations 108 and 109, for example, to the correlation degrees Q_j obtained for each projection point T_j on the projection point

10 series.

[Equation 108]

$$\tilde{\beta}_j = \frac{1}{Q_j}$$

[Equation 109]

$$\beta_j = \frac{\beta_j}{\sum_{j=1}^{M} \tilde{\beta}_j}$$

15   Basically, the existence probability β_j only needs to satisfy the equation 106 and the equation 107. Therefore, for the conversion processing, equations other than the equation 108 and the equation 109 can be used.

20   After determining the existence probability β_j of each projection point T_j by the step 10305f, the color information T_j and the existence probability β_j of each projection point T_j are stored in the area kept in the step 10304.

25   After storing the color information K_j and the existence probability β_j of each projection point T_j, the projection point series is updated and it is checked whether processing from the step 10305c to the step 10305f has been performed for

30 every projection point series determined in the step 10303 (step 10305g). When there is any projection

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point series for which processing from the step
10305c to the step 10305f has not been performed,
the step returns to the step 10305b so that the
processing from the step 10305c to the step 10305f

5　is repeated.

Accordingly, after the processing from the
step 10305c to the step 10305f are performed for
every projection point series determined in the step
10303, the processing of the step 10305 completes,

10　so that the three-dimensional shape of the object
can be obtained.

By performing the processing of the step
103, the texture array of each projection point
$T_j(j=1,2,…,M)$ on the projection point series stores

15　the color information K_j and the existence
probability β_j as shown in Fig.97, for example.
That is, as to the three-dimensional shape of the
object obtained by the three-dimensional image
display method of the present invention, the surface

20　of the object exits not only on one projection point
on the projection point series as is in the
conventional method, but the surface of the object
exits on each projection point. In the three-
dimensional image display method in the present

25　invention, two-dimensional images to be displayed on
each of the plural image display planes are
generated using the three-dimensional shape of the
object (step 104).

When generating the two-dimensional images

30　to be displayed on each image display planes in step
104, the viewpoint of the observer, plural two-
dimensional image generation planes, and the three-
dimensional shape of the object obtained in the step
103 are set, first. In this step, the two-

35　dimensional image generation planes $LD_n(n=1,2,…,N)$
are set such that they overlap with each other in
the depth direction from the viewpoint P of the

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observer as shown in Fig.98, for example. In addition, the distance ld_n from the viewpoint P of the observer to the two-dimensional image generation plane LDn is set such that it becomes the distance

5 set in the step 102. At this time, if the number of projection planes L_j representing the three-dimensional shape of the object and the placement intervals are the same as the number of the two-dimensional image generation planes LD_n and the

10 placement intervals, the three-dimensional shape of the object is set such that the projection planes L_j becomes the same as the two-dimensional image generation planes LD_n. In this case, when the two-dimensional image generation planes LD_n are planes

15 for generating the images displayed on the image display planes of the brightness modulation type DFD, it is necessary to determine the color information KD_n and the brightness distribution coefficients Y_n for points (display points) A_n, on the two-

20 dimensional image generation plane LD_n, that overlap viewed from the viewpoint P of the observer. As shown in Fig.98, when the projection planes L_j representing the three-dimensional shape of the object are the same as the two-dimensional image

25 generation planes LD_n, the color information KD_n of each display point A_n is determined to be the color information K_j of the projection point T_j on the projection plane L_j that is overlapping the two-dimensional image generation plane LD_n on which the

30 display point A_n exists. In addition, the brightness distribution ratio Y_n of the display point A_n is determined to be the existence probability β_j of the projection point T_j on the projection plane L_j that is overlapping the two-

35 dimensional image generation plane LD_n. After the color information KD and the brightness distribution coefficient γ are determined for each display point

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A on the two-dimensional image generation planes LD_n, the images generated on the two-dimensional image generation planes LD_n are output and are displayed on the image display planes of the actual DFD (step

5   105).

However, it is not necessary that the number and placement intervals of the projection planes L_j for representing the three-dimensional shape of the object are the same as the number and

10   placement intervals of the two-dimensional image generation plane LD_n. Therefore, next, another method for generating the two-dimensional images are described in a case where the number and placement intervals of the projection planes L_j for

15   representing the three-dimensional shape of the object are not the same as the number and placement intervals of the two-dimensional image generation plane LD_n.

In this case, when the distance from a

20   projection plane closest to the viewpoint P of the observer to a projection plane farthest from the viewpoint P is almost the same as the distance from a two-dimensional image generation plane closest to the viewpoint P to a two-dimensional image

25   generation plane farthest from the viewpoint P, the projection planes L_j representing the three-dimensional shape of the object are set such that the projection plane L_1 farthest from the viewpoint P of the observer and the two-dimensional image

30   generation plane LD_1 overlap as shown in Fig.99, for example. By doing so, color information and brightness distribution coefficients γ of each display point A on the two-dimensional image generation plane LD_1 farthest from the viewpoint P

35   of the observer become the color information K and the existence probability β of each projection point T on the projection plane L_1 farthest from the

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viewpoint P of the observer.

   Color information and brightness KD
distribution coefficients γ of each display point A
on the two-dimensional image generation plane LD
5   which does not overlap any projection plane are
determined in the following method.

   As to the color information and brightness
KD distribution coefficients γ of the display point
A on the two-dimensional image generation plane LD
10   which does not overlap any projection plane, color
information K and existence probability β of the
projection points T, on projection planes L,
overlapping with the display point when viewed from
the viewpoint P of the observer are assigned to the
15   projection point A on the two-dimensional image
generation plane LD closest for the projection
planes L. In this case, the color information KD of
the display point A is determined to be an average
value of assigned color information K of projection
20   points T, or to be color information L of the
projection point T on the projection plane L closest
to the two-dimensional image generation surface LD.
The brightness distribution coefficient γ is
determined to be a sum of pieces of assigned
25   existence probabilities β of each projection point T.
In this case, assuming that a set of projection
planes L_j to which the two-dimensional image
generation plane LD_n is the closest is $\{L_j | j \in \Gamma_n\}$,
the brightness distribution ratio γ_n of the display
30   point A_n on the two-dimensional image generation
surface LD_n is provided by the following equation
110 using the existence probability β_j of the
projection point T_j of the projection plane L_j.
   [Equation 110]

35
$$\gamma_n = \sum_{j \in \Gamma_n} \beta_j$$

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In the following, a case where position relationship between the projection planes L_j and the two-dimensional image generation planes LD_n is as shown in Fig.100A is considered. Assuming that
5   color information K_j and each existence probability β_j of each of projection points T_j $(j=1,2,3,4,5)$ overlapping with the display points A_1 and A_2 when viewed from the viewpoint P of the observer are assigned to a display point A on a two-dimensional
10   image generation plane that is closest for the projection planes, color information and existence probabilities of the projection points T_1, T_2 and T_3 are assigned to the display point A_1. In this case, the color information of the display point A_1 may be
15   an average value of the color information K_1, K_2 and K_3 of the projection points T_1, T_2 and T_3, for example, or may be the color information K_2 of the projection point T_2 closest from the viewpoint of the display point A_1. The brightness distribution
20   coefficient γ_1 of the display point A_1 is determined to be a sum of the existence probabilities β_1, β_2 and β_3 of the projection points T_1, T_2 and T_3 using the equation 110.

    In the same way, color information and
25   existence probabilities of the projection points T_4 and T_5 are assigned to the two-dimensional image generation plane LD_2. In this case, the color information KD_2 of the display point A_2 may be an average value of the color information K_4 and K_5 of
30   the projection points T_4 and T_5, or may be the color information K_5 of the projection point T_5. The brightness distribution coefficient γ_2 is determined to be a sum of the existence probabilities β_4 and β_5 of the projection points T_4 and T_5 using the equation
35   110.

    When the placement intervals of the two-dimensional image generation plane LD_n and the

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placement intervals of the projection planes L_j are different, color information and existence probability of the projection point on a projection plane L_j existing between two successive two-

5　dimensional image generation plane LD_n and LD_{n+1} can be distributed in a ratio of the distances of the two two-dimensional image generation plane LD_n and LD_{n+1}. In this case, assuming that a set of the projection planes L_j between the two-dimensional

10　image generation planes LD_n and LD_{n+1} is $\{L_j | j \in \Gamma_n\}$, the brightness distribution ratio γ_n of the display point A_n on the two-dimensional image generation plane LD_n can be calculated by the following equation 111 using the existence probability β_j of

15　each projection points T_j.

[Equation 111]

$$\gamma_n = \sum_{j \in \Gamma_n} w_{j,n} \beta_j$$

In the equation 111, $w_{j,n}$ is a coefficient indicating a degree of contribution of the projection plane L_j

20　to the two-dimensional image generation surface LD_n.

　　　　A case where projection planes L_1 and L_2 are set between the two-dimensional image generation planes LD_1 and LD_2 is considered as shown in Fig.100B, for example. In this case, assuming that distances

25　from the projection plane L_1 to the display planes LD_1 and LD_2 are B_1 and B_2 respectively, the degrees $w_{1,1}$ and $w_{1,2}$ of contribution of the projection plane L_1 to the two-dimensional image generation planes LD_1 and LD_2 can be provided by the following equation

30　112.

[Equation 112]

$$w_{1,1} = \frac{B_2}{B_1 + B_2}, \quad w_{1,2} = \frac{B_1}{B_1 + B_2}$$

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In the same way, when distances from the projection
plane L_2 to the two-dimensional image generation
planes LD_1 and LD_2 are B_3 and B_4 respectively, the
degrees $w_{2,1}$ and $w_{2,2}$ of contribution of the
5   projection plane L_2 to the two-dimensional image
generation planes LD_1 and LD_2 can be provided by the
following equation 113.

[Equation 113]

$$w_{2,1} = \frac{B_4}{B_3 + B_4}, \quad w_{2,2} = \frac{B_3}{B_3 + B_4}$$

10   As a result, each of the brightness
distribution ratio γ_1 of the display point A_1 of the
two-dimensional image generation plane LD_1 and the
brightness distribution ratio γ_2 of the display
point A_2 of the two-dimensional image generation
15   plane LD_2 is shown in the following equation 114.

[Equation 114]

$$\gamma_1 = w_{1,1} \beta_1 + w_{2,1} \beta_2, \quad \gamma_2 = w_{1,2} \beta_1 + w_{2,2} \beta_2$$

As mentioned above, when obtaining the three-
dimensional shape of the object, a shape is obtained
20   in which the probability (existence probability) β_j
that the surface of the object exists on each
projection point T_j is provided from the correlation
degree Q_j of the projection point T_j on the
projection point series. Then, the brightness
25   distribution coefficient of the display point A on
the two-dimensional image generation plane LD is
provided as the existence probability β_j.
Accordingly, when there is no projection point
having the correlation degree Q_j of a distinctive
30   value in the projection points T_j on the projection
point series, so that reliability for estimation of
the distance of the surface of the object is low,
the surface of the object is represented vaguely on

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plural projection planes on the projection point series. Then, the brightness distribution coefficient γ of the point on the two-dimensional image generation plane LD is determined from the

5   existence probability β of each projection point T_j. Accordingly, when the two-dimensional images generated on the two-dimensional image generation planes are displayed on the actual image display planes so as to present the three-dimensional image

10   of the object, the surface of the object is displayed vaguely on the projection point series in which reliability for distance estimation is low and the existence probability β is dispersed to plural projection points. Therefore, a noise on the three-

15   dimensional image displayed on the DFD becomes inconspicuous so that an image that looks natural for the observer can be displayed.

As described above, according to the image generation method of this embodiment 5-1, the three-

20   dimensional image that looks natural for the observer can be displayed without obtaining the accurate three-dimensional shape of the object to be displayed.

In addition, in the image generation

25   method of this embodiment 5-1, although a case is described as an example in which a color image in which the point (pixel) is represented by color information using three primary color of red (R), green (G) and blue (B) is obtained and the three-

30   dimensional shape of the object is generated, the image to be obtained is not limited to the color image. In the image generation method of this embodiment 5-1, a black and white image in which the point (pixel) is represented by brightness (Y) and

35   color-difference (U,V) may be obtained to obtain the three-dimensional shape of the object. In the case when the image to be obtained is the black and white

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image, the three-dimensional shape can be obtained
by the procedure described in the embodiment 5-1
using the brightness information (Y) as information
corresponding to the color information so that the
5   two-dimensional images can be generated.
        (Embodiment 5-2)
            Figs.101-104 are schematic diagrams for
explaining the three-dimensional image generation
method of the embodiment 5-2. Fig.101 is a diagram
10   showing relationship between the projection point
and the corresponding point. Fig.102 is a flow
diagram showing an example of steps for determining
the color information and the existence probability
of the projection point. Figs.103 and 104 are
15   diagrams for explaining a method for obtaining the
existence probability.
            The basic procedure of the image
generation method of this embodiment 5-2 is the same
as the three-dimensional image generation method of
20   the embodiment 5-1, and processing from the step 101
to the step 105 shown in Fig.90 are performed. The
different point of the three-dimensional image
generation method of this embodiment 5-2 compared to
the three-dimensional image generation method of the
25   embodiment 5-1 is that plural images of different
focusing distances are obtained instead of the
plural images of different viewpoints in step 101,
and the three-dimensional shape of the object is
obtained using the images having different focusing
30   distances in the step 103.
            For displaying the three-dimensional image
of the object on the DFD using the three-dimensional
image generation method of the embodiment 5-2,
plural images are taken from a viewpoint while
35   changing the focusing distance, first. At this time,
the plural images are taken using the polarizing
binary optical system, a variable focus lens and the

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like, for example. The image to be obtained may be a color image in the same way as the embodiment 5-1 or may be a black and white image. Next, as described in the embodiment 5-1, after setting the
5   viewpoint of the observer (step 102), processing of the step 103 for obtaining the three-dimensional shape of the object is performed.

In the processing of the step 103, as described in the embodiment 5-1, projection planes
10   $L_j(j=1,2,…,M)$ and the reference viewpoint R are set first (step 10301, step 10302). Then, next, the projection point series and the corresponding points are set, and the array (area) for storing the information of the projection plane is kept (step
15   10303, step 10304).

In the three-dimensional image display method of this embodiment 5-2 in which the three-dimensional image of the object is displayed using plural images having different focusing distances,
20   when setting the projection planes L_j in step 10301, the planes are set such that the distances from the viewpoint c of the camera are the same as the focusing distances $f_i(i=1,2,…,N)$ of the images taken by the camera as shown in Fig.101, for example.
25   Then, in the step 10303, the corresponding points G_i corresponding to the projection point T_j are determined to be points, on images Img_i, overlapping with the projection point T_j when viewing the projection point T_j from the viewpoint C of each
30   camera. Methods for setting the projection point series, and for associating the coordinates of the projection point T_j with the digital image coordinates of the corresponding point G_i are the same as the methods described in the embodiment 5-1.
35   Thus, detailed descriptions are not provided here.

In addition, the processing for keeping the area for storing the information of the

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projection planes in the step 10304 is also the same
as that described in the embodiment 5-1. Thus,
detailed descriptions are not provided here.

　　Next, the color information and the
5　existence probability information of each projection
point T_j are determined using the obtained plural
images (step 10305). Also in the three-dimensional
image display method of this embodiment 5-2, in the
step 10305, double loop processing is performed in
10　which processing for determining the color
information and the existence probability of each
projection point T_j on the projection point series
is repeated for every projection point series. Thus,
first, the projection point series is initialized
15　(step 10305a). Then, next, the projection point T_j
on the projection point series is initialized to $j=1$,
for example (step 10305b).

　　Next, the color information of the
projection point T_j is determined (step 10305c). In
20　the step 10305c, an average value of·color
information of the corresponding points G_i set in
the step 10303 is determined to be the color
information K_j of the projection point T_j.

　　Next, the focusing degree Q_j of the
25　projection point T_j is obtained based on degree
(focusing degree) by which focus is achieved for a
point, of the object, appearing on each
corresponding point G_i corresponding to the
projection point T_j (step 10305j). The focusing
30　degree can be determined according to sharpness or
blurriness at a point or a small region on the image.
As a calculation method for the focusing degree,
there are various methods based on Depth from Focus
theory or Depth from Defocus theory. The focusing
35　degree Q_j can be obtained by comparing sizes of
local spatial frequency of each corresponding point
G_i, for example.

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The Depth from Focus theory or the Depth from Defocus theory is a method for analyzing plural images having different focusing distance to measure the surface shape of the object. In the method, the
5　surface of the object is estimated to exist at a distance corresponding to a focusing distance of an image having the highest local spatial frequency among the images taken by changing the focusing distance, for example. Thus, the focusing degree Q_j
10　of the projection point T_j is calculated using an evaluation function of the local spatial frequency represented by the following equation 115, for example.

[Equation 115]

$$Q = \frac{1}{D} \sum_{x=x_i}^{x_f} \sum_{y=y_i}^{y_f} \left\{ \sum_{p=-L_c}^{L_c} \sum_{q=-L_r}^{L_r} |f(x,y) - f(x+p, y+q)| \right\}$$

wherein f indicates a gray scale of a pixel, D indicates a constant for normalization that is a number of all pixels, (-Lc, -Lr)-(Lc, Lr) and (xi, yi)-(xf, yf) indicate small regions for performing
20　distribution evaluation and smoothing respectively.

The equation 115 is one example for a method for obtaining the focusing degree Q_j, and the focusing degree Q_j can be obtained by using equations other than the equation 115.

25　After obtaining the focusing degree Q_j by the step 10305h, the projection point T_j is updated, and it is checked whether processing of the steps 10305c and 10305h are performed for every projection point on the projection point series that is a
30　subject for processing (step 10305e). When there is any projection point for which the processing of the steps 10305c and 10305h has not been performed, the step returns to the step 10305c so that the color information K_j and the focusing degree Q_j are

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obtained.

When the color information and the focusing degree Q_j are obtained for every projection point on the projection point series that is a

5 subject of processing, color information K_j and the focusing degree Q_j are provided for each projection point T_j on the projection point series as shown in Fig.103. The focusing degree Q_j of the projection point T_j is a degree corresponding to the

10 correlation degree used for determining the existence probability β in the embodiment 5-1. There may be a case where there is no projection point at which the focusing degree has the distinctive small value when the focusing degrees Q_j

15 of each projection point T_j on the projection point series are compared depending on the shape of the object, the texture of the surface, photographing conditions and the like. In this case, even if the surface of the object is estimated to exist at a

20 projection point, the reliability is low and there is a case the estimation is erroneous. When the estimation is erroneous, the effect appears as a large noise on the generated image.

Thus, according to the three-dimensional

25 image display method of this invention, next, the probability (existence probability) $β_j$ that the surface of the object exists on each projection point T_j on the projection point series is determined (step 10305f). In this case, it is

30 necessary that the existence probability $β_j$ satisfies the equations 106 and 107. Thus, in this embodiment 5-2, the existence probability $β_j$ of the projection point T_k is determined using the equation 116, for example.

35 [Equation 116]

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$$\beta_k = \frac{Q_k}{\displaystyle\sum_{j=1}^{M} Q_j}$$

Basically, it is only necessary that the existence probability β_j satisfies the conditions of the equations 106 and 107. Therefore, the existence
5   probability β_j can be determined using equations other than the equation 116.

After calculating the existence probability β_j in step 10305f as shown in Fig.104, next, the color information K_j and the existence
10   probability β_j of each projection point T_j are stored in the area kept in the step 10304.

After storing the color information K_j and the existence probability β_j of each projection point T_j, the projection point series is updated and
15   it is checked whether processing from the step 10305c to the step 10305f has been performed for every projection point series determined in the step 10303 (step 10305g). When there is any projection point series for which processing from the step
20   10305c to the step 10305f has not been performed, the step returns to the step 10305b so that the processing from the step 10305c to the step 10305f is repeated.

Accordingly, after the processing from the
25   step 10305c to the step 10305f are performed for every projection point series determined in the step 10303, the processing of the step 10305 completes, so that the three-dimensional shape of the object can be obtained. Then, after obtaining the three-
30   dimensional shape of the object by the processing of the step 103, color information and the brightness distribution coefficient γ of the display point A on the two-dimensional image generation plane LD are

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determined based on the three-dimensional shape of the object, so as to generate the two-dimensional images to be displayed on the plural overlapping image display planes such as the DFD according to

5 the same procedure as the embodiment 5-1 (step 104). Then, by displaying the generated images on actual image display planes (step 105), the three-dimensional image of the object can be presented.

Also in the three-dimensional image

10 display method of this embodiment 5-2, like the three-dimensional image display method of the embodiment 5-1, when there is no projection point having the focusing degree Q_j of a distinctive value in the projection points T_j on the projection point

15 series, so that reliability for estimation of the distance of the surface of the object is low, the surface of the object is represented vaguely on plural projection planes on the projection point series. Then, the brightness distribution

20 coefficient γ of points on the two-dimensional image generation plane LD is determined from the existence probability β of each projection point T_j. Accordingly, when the two-dimensional images generated on the two-dimensional image generation

25 planes are displayed on the actual image display planes so as to present the three-dimensional image of the object, the surface of the object is displayed vaguely on the projection point series in which reliability for distance estimation is low and

30 the existence probability β is dispersed to plural projection points. Therefore, a noise on the three-dimensional image displayed on the DFD becomes inconspicuous so that an image that looks natural for the observer can be displayed.

35 As described above, according to the three-dimensional image generation method of this embodiment 5-2, the three-dimensional image that

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looks natural for the observer can be displayed
without obtaining the accurate three-dimensional
shape of the object to be displayed.

5   In addition, also in the case of the image
generation method of this embodiment 5-2, the image
to be obtained may be either of the color image or a
black and white image. When using the black and
white image, processing described in this embodiment
5-2 is performed using the brightness information
10   (Y) as the information corresponding to the color
information.

(Embodiment 5-3)

Also in this embodiment, a three-
dimensional image generation apparatus having a
15   configuration similar to that shown in Fig.85 in the
fourth embodiment can be provided. In addition, an
image display system having a configuration similar
to that shown in Figs.87-89 in the fourth embodiment
can be provided. In the configurations of this
20   embodiment, processing performed by the apparatuses
corresponds to the embodiments 5-1 and 5-2.

As mentioned above, although the present
invention is described concretely based on
embodiments, the present invention is not limited to
25   the specifically disclosed embodiments, and
variations and modifications may be made without
departing from the scope of the invention.

For example, although a method for
displaying the three-dimensional image of the object
30   based on images of different viewpoints is described
in the embodiments 5-1, and a method for displaying
the three-dimensional image of the object based on
images having different focusing distances is
described in the embodiment 5-2, the three-
35   dimensional image of the object can be displayed by
combining these methods. In this case, the
correlation degree is obtained from corresponding

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points of images of different viewpoints with respect to a projection point T_j, the local space frequency is obtained from corresponding points of images taken by changing focal positions from a

5　viewpoint, and the existence probability β_j is obtained by combining them.　By doing so, the reliability of the existence probability β_j increases so that an image that looks natural for the observer can be displayed.

10　(Effects of the fifth embodiment)

Also in the three-dimensional image generation method of the fifth embodiment, when viewing a direction from the reference viewpoint, even when the reliability for estimating a distance

15　(projection point) at which the object surface exists is low, the surface of the object exists with a probability on the projection point at which the surface of the object actually exists.　As a result, by displaying each point on the image display plane

20　with brightness according to the existence probability, discontinuous noise that may occur in the conventional method when erroneous distance estimation is performed can be made inconspicuous. In addition, even by an apparatus having low

25　processing performance such a generally used personal computer, each two-dimensional image can be generated at high speed.

The present invention is not limited to the specifically disclosed embodiments, and

30　variations and modifications may be made without departing from the scope of the invention.

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